MATERIALS and PROCESSES

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In memory of
Dr. A. R. STEVENSON, Jr.

PREFACE TO THE FIRST EDITION

This book has been written to present in one volume a broad study of the materials and manufacturing processes employed by the design engineer, and thus to provide information directly useful in the selection of materials for design. It is intended for convenient reference and for textbook use. It has therefore been organized for ease in classroom presentation and in such a manner that, it is hoped, will give the practicing engineer or designer an over-all picture of the subjects discussed.

The problem of selecting the material for a piece of apparatus is no easy matter. One's first attempt at selection proves this quite convincingly. Plenty of information is available, but the real task is to find and evaluate that which has a bearing on the design. It is reasonable to assume that, if a material has the properties required in service, it is suitable, and so it may be selected. It soon becomes clear, however, that *the* material also must be available in the right form, and be such that it lends itself better than others to the available and desired method of processing. In addition, the over-all cost, including both of the material and of fabricating it, should represent the maximum value per dollar expended. And this combination can be obtained only when the product is both proportioned with respect to the material to be used and detailed to accommodate the method of processing.

The young engineer's training for design, which is largely obtained through working with more experienced engineers, should be preceded by some study of metallic and nonmetallic materials and of manufacturing methods. However, much of the available information on these subjects is not presented to suit the requirements of the design engineer. Data on metallic materials are presented largely from the metallurgist's viewpoint, and information on manufacturing methods usually tells how to accomplish the process and how to operate the equipment used. These approaches leave a rather broad gap in the design problem, a gap that it is hoped this book will bridge.

This textbook considers chiefly the materials and processes used in manufacturing electromechanical products. Sufficient metallurgy is included to enable the engineer to understand heat-treating prac-

tice and the effects of various processes on metallic materials. In the discussion of processes, enough detail for understanding the basic nature of each process is given; but—throughout—emphasis is laid on so designing the products that they can be easily processed Materials and processes used only in building construction are not considered. Material-specifications systems and data have been left out also because of their changing nature and the impossibility of covering adequately all sources of supply.

Many of the chapters have been written from lectures given in a general course in materials and processes conducted in the Advanced Engineering program of the General Electric Company. I am indebted to the many engineers whose lectures and papers have been used in the preparation of this book, and, in so far as practicable, their names appear at the head of those chapters prepared from their lectures or incorporating their work. I also wish to express my appreciation to Dr. A. R. Stevenson, Jr., to whom this book is dedicated, for the opportunity of preparing the book and for his encouragement; to Mr. E. E. Parker, Mr. E. R. Boynton, and Mr. J. E. Ryan, who served as the first supervisors of the general course and laid out the early lectures; to Mr. T. S. Fuller and Mr. E. R. Parker for their helpful suggestions and consultation; and to Miss F. E. Rist for her patience and good nature in typing the manuscript and in proofreading.

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CONTENTS

PART ONE MATERIALS

PART TWO PROCESSES

PART ONE

Materials

1 THE NATURE
OF PURE METALS

1.1 INTRODUCTION

Some forty chemical elements of commercial importance are customarily classed as *metals*. They are distinguished from other elements by characteristic physical properties, or *metallic properties*, such as high melting temperature, low specific heat, good electrical and thermal conductivity, *metallic luster*, hardness, and the ability to be deformed permanently without fracture.

All the elements classed as metals do not possess these properties in equal measure. Some are notable in lacking one or more of the metallic properties entirely (see Table 1.1). The classification of metals is therefore not an exact one. and some exceptions are made.

Except for copper, the precious metals, and some iron in meteorites, all the metals are found in nature chemically combined with other elements as *ores*. The science of extracting them, refining them, and adapting them to use is known generally as *metallurgy*. *Process metallurgy* deals with the purification and reduction of ores and with the refining, working, and heat treatment of the metallic materials obtained. *Physical metallurgy* covers the study of the fundamental nature of metallic materials and leads to the development of new materials and processing techniques on which engineering progress relies heavily.

In modern industry the engineer and the manufacturer must have a working knowledge of physical metallurgy—the engineer so that he may be guided in the selection and effective utilization of materials, and the manufacturer so that he will appreciate the purpose and exactness of processing techniques, and avoid waste and spoilage due to misuse of material. This chapter is therefore devoted to the physical metallurgy of pure metals. It, together with Chapters 2 and 3, forms the background on which the remaining discussions of metallic materials and processes will be based.

1.2 METALLIC MATERIAL

In chemistry all matter is said to be composed of molecules, each containing one or more smaller units called *atoms*, which are present in some arrangement characteristic of the molecule. The functioning units in metals, however, are single atoms. Metallurgists therefore consider the atom to be the fundamental unit of metallic material, and the term "molecule" is not used in describing metallic structure.

It is convenient for most purposes in physical metallurgy to think of the atom as a functioning unit of very small size, shaped something like a ball. Occasionally it is helpful to use the physicist's picture of the atom as being composed of a heavy nucleus of protons and neutrons surrounded by a cloud of electrons. The nucleus contains most of the mass. The cloud of electrons forms the ball-like exterior.

Electrons in the electron cloud are always in motion. They spin about their own axes and in orbits around the nucleus. Temperature changes cause alterations in these motions, and the orbits are modified by the presence of neighboring atoms.

The electron orbits around the nucleus may be visualized as portions of concentric shells. Only a limited number of electrons may exist at each shell diameter, viz., two on the first, eight on the second, etc. The number of orbit shells is thus determined by the atomic number of the element.

The outer electron shell of metal atoms generally has less electrons than the limiting number, and these usually act as excess electrons. This gives a structural insufficiency to the atom as a whole. In pure metals the atom has the tendency to obtain symmetry and stability by sharing its free electrons with other like atoms, which contribute their free electrons to the electron cloud. The presence of such free electrons accounts for the ability of metal atoms to associate with others, and for their electrical and thermal conductivity. It also accounts for the Seebeck effect,* emissivity, optical reflection, and contact potential effects.

1.3 METALLIC STATES

A metal can exist as a solid, a liquid, or a vapor (gas). The state depends on the pressure exerted on the metal and on its temperature.

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* If two wires are connected in a circuit, and one junction is maintained at a higher temperature than the other, a voltage is developed that causes current to flow through the circuit.

The pressure vs. temperature diagram for a pure metal has the form illustrated in Fig. 1.1.

The three lines define the pressure-temperature regions for each state. These lines also indicate the pressures and temperatures at which the respective states may coexist. All three states may. exist together at the "triple point" where the three lines intersect.

Values for the triple point and the state curves are characteristic of each metal. But all the common metals are solid at atmospheric
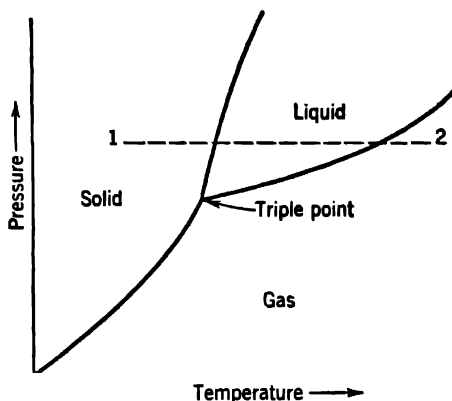

FIG. 1.1.   State of a pure metal vs. pressure and temperature.

pressure and temperature, except mercury, which is liquid. All except arsenic change to liquid and thence to vapor as the temperature is increased (line 1–2, Fig. 1.1).

Arsenic will change directly from a solid to vapor at atmospheric pressure as its temperature is raised. This process is known as *sublimation*. A common example of it is the wasting away of mothballs. All the common metals will sublime at very low pressures, such as those used in vacuum tubes, if their temperatures are raised sufficiently.

1.4   VAPOR AND VAPOR PRESSURE

The vapor pressure of a metal is the pressure of its vapor over a solid (or a liquid) established by the equilibrium of the atoms entering and those leaving the solid (or the liquid). If the metal is placed in an evacuated space, the vapor pressure is the only pressure. But when the metal is open to atmosphere, the vapor pressure constitutes a partial pressure of that exerted on the solid (or liquid) surface.

The vapor pressures of metals at atmospheric temperature are not large. That for tungsten has been calculated to be 10^{-149} atmospheres. This is equivalent to less than one atom in a volume equal to that of the universe! Although tungsten is somewhat less volatile than most metals, all are of low vapor pressure, and even mercury has only one ten-thousandth the vapor pressure of water at 30 C.

Although metals volatilize at a more rapid rate at high temperatures, the vapor pressures for most common metals are not of practical importance at the temperatures used in commercial metallurgical practice. But such metals as mercury, zinc, cadmium, and arsenic are exceptions. The vapor pressure of mercury is high enough at relatively low temperatures so that the properties of its vapor are successfully utilized for power generation in a vapor turbine. Zinc, arsenic, antimony, and even magnesium have high enough vapor pressures at high temperatures for purification by condensation on a commercial scale.

1.5 LIQUID METAL

The atoms within a liquid do not take fixed positions, nor is their arrangement as chaotic as in a vapor. The atoms are restrained in their motion by their neighbors and, of course, by the walls of the containing vessel. Some liquid metals show preferences for characteristic distances between their atoms.

Atoms continually leave and reenter the surface of a liquid metal, as described in paragraph 1.4. The pressure of the atoms above the liquid surface at any time is increased with increasing temperature. When the temperature has been increased until the vapor pressure equals the externally applied pressure, the passage of atoms from the liquid induces a mechanical agitation known as *boiling*.

The temperatures at which the common metals boil at atmospheric pressure are given in Table 1.1. If the external pressure is lowered, the boiling temperatures are lowered, as illustrated in Fig. 1.1. Since the pressure on any part of the liquid metal is the sum of the external pressure on the surface and the weight of the liquid column it supports, the boiling action takes place almost exclusively at the surface at low pressures. Even at atmospheric pressure boiling takes place closer to the surface for metals than for water.

1.6 SOLIDIFICATION

As a liquid metal cools, the motion of the atoms becomes slower and slower until the *freezing point* is reached. The *random* motion

Table 1.1 Metallic Elements of Commercial Importance

Metal	Chemical Symbol	% Wt of Earth's Crust *	Specific † Gravity	Melting ‡ Pt., °F	Boiling ‡ Pt., °F	Specific ‡ Heat at 32 F vs. Water	Electrical § Resistivity, microhm-cm	Thermal ‡ Conductivity, Btu/ft²/in./°F/sec
Aluminum	Al	8.13	2.7	1220	3740	0.215	2.655	0.43
Antimony	Sb		6.71	1167	2620	0.049	39.0 (0C)	0.037
Arsenic	As	0.0000001	5.73	..	1130 ‖	0.082	35 (0C)	..
Barium	Ba	0.05	3.7	1300	2980	0.068	..	.
Beryllium	Be	0.001	1.93	2340	5020	0.52	5.9 (0C)	0.31
Bismuth	Bi	.	9.92	520	2590	0.034	106.8 (0C)	0.016
Cadmium	Cd	.	8.7	610	1409	0.055	6.83 (0C)	0.18
Calcium	Ca	3.63	1.55	1560	2625	0.149	3.43 (0C)	0.24
Cerium	Ce	.	6.8	1100	2550	0.042	78	..
Chromium	Cr	0.037	7.1	3430	4500	0.11	13 (28C)	0.13
Cobalt	Co	0.001	8.92	2723	5250	0.099	6.24	0.134
Columbium	Cb	..	8.4	4380	5980	0.065	13.1	.
Copper	Cu	0.01	8.94	1980	4700	0.092	1.673	0.759
Germanium	Ge		5.36	1760	5070	0.073	89,000 (0C)	.
Gold	Au	0.0000001	19.37	1945	5380	0.031	2.19 (0C)	0.57
Iridium	Ir	..	22.42	4449	9600	0.031	5.3	0.11
Iron	Fe	5.01	7.88	2802	4960	0.11	9.71	0.144
Lead	Pb	0.002	11.35	621	3160	0.031	20.65	0.067
Lithium	Li	..	0.59	367	2500	0.79	8.55 (0C)	0.14
Magnesium	Mg	2.09	1.74	1202	2030	0.25	4.46	0.303
Manganese	Mn	0.1	7.39	2273	3900	0.115	185	..
Mercury	Hg	0.00001	15.63	−38	675	0.033	94.1 (0C)	0.0163
Molybdenum	Mo	0.0001	10.2	4760	8670	0.061	5.17 (0C)	0.28
Nickel	Ni	..	8.91	2651	4950	0.105	6.84	0.18
Palladium	Pd	..	12.16	2829	7200	0.058	10.8	0.135
Platinum	Pt	..	21.7	3224	7970	0.032	9.83 (0C)	0.133
Potassium	K	2.6	0.875	145	1420	0.177	6.15 (0C)	0.19
Rhodium	Rh	..	12.5	3571	8100	0.059	4.5	0.17
Selenium	Se	..	4.8	428	1260	0.084	..	..
Silicon	Si	27.72	2.34	2605	4200	0.162	100,000 (0C)	0.16
Silver	Ag	0.000001	10.75	1761	4010	0.056	1.59	0.81 (0C)
Sodium	Na	2.85	0.97	208	1638	0.295	4.2 (0C)	0.26
Strontium	Sr	..	2.54	1420	2520	0.176	23	
Tantalum	Ta	.	16.6	5425	7590	0 036	12.4	0.11
Tin	Sn	0.0000001	7.30	449	4120	0.054	11.5	0 127
Titanium	Ti	0.63	4.5	3300	5430	0.126	80 (0C)	.
Tungsten	W	0.005	20.2	6170	10700	0.032	5.5	0 39
Uranium	U	..	18.69	2065	5250	0 028	60	0.052
Vanadium	V	..	5.7	3150	6150	0.120	26	.
Zinc	Zn	0.004	7.13	787	1663	0.0915	5.916	0.22
Zirconium	Zr	..	6.4	3200	5250	0.066	41 (0C)	.

Properties are for annealed metals of high purity. Impurities and strain from working or heat treatment can alter these properties considerably.

* Layer land and ocean, 3 miles deep, according to U. S. Geological Survey (0.0000001% = 24,500,000 tons).

† S.g. × 0.0362 = lb per cu in. at room temperature.

‡ At atmospheric pressure; from *Metals Handbook*, A.S.M., 1948.

§ At room temperature; from *Metals Handbook*, A.S.M., 1948.

‖ Point of sublimation at atmospheric pressure.

of the atoms stops at this temperature, and the atoms take fixed locations with regard to one another, forming a solid metal. All the atomic motion does not cease as a result of solidification, but that motion which persists is confined to vibration within these fixed locations. A further decrease in temperature will cause some modification of this atomic vibration, in keeping with a lower energy state.

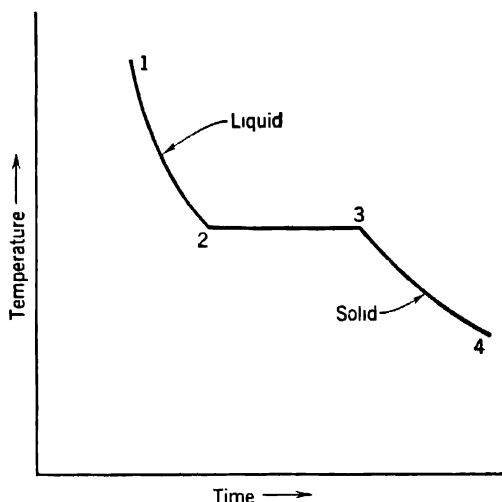If heat is ideally removed at a constant rate during freezing, the

FIG. 1.2   Ideal cooling curve for freezing of a pure metal.

cooling curve (temperature vs. time) will be similar to that shown in Fig. 1.2. Cooling of the liquid is indicated by the line from point 1 to point 2. At point 2 freezing begins, and constant temperature is maintained until freezing is complete at point 3. Continuing the removal of heat from the now solid metal causes the drop in temperature 3 to 4. Note that during the time interval 2–3 the temperature remained constant, although heat was being removed at a constant rate. The heat energy given up during this interval is called the latent heat of fusion. It is supplied by the atoms as they take fixed positions and lose their kinetic energy of random motion.

1.7   SOLID METAL

The atoms of solid metal are held together by the electrostatic attraction between the positive ions in the nucleus and the negative electron cloud. Since these forces are greater in some directions than

in others, the atoms arrange themselves in geometric patterns or structures characteristic of the metal.

Such structures are described by *space lattices,* which are formed by three-dimensional nets of intersecting straight lines. They divide space into equal prisms called *unit cells.* Every intersection in the lattice (and in a unit cell) has an identical grouping of other lattice intersections about it. These intersections may be positions of atoms in the metal, or they may be points about which more than one atom is clustered.

Although there are fourteen types of space lattices, the structures of most common metals follow one of three lattice types. They are body-centered cubic, face-centered cubic, and simple hexagonal (for the hexagonal, close-packed structure). Table 1.2 lists several metals and their corresponding lattice types at room temperature.

Table 1.2   Lattice Types for Several Metals at Room Temperature

Body-Centered Cubic	Face-Centered Cubic	Simple Hexagonal (Close Packed)
Barium	Aluminum	Beryllium
Chromium	Calcium	Cadmium
Columbium	Copper	Cobalt
Iron	Gold	Magnesium
Molybdenum	Lead	Titanium
Tantalum	Nickel	Zinc
Tungsten	Platinum	Zirconium
Vanadium	Silver	

A number of metals exist in one lattice form over a range of temperature, but at a certain temperature the lattice form changes to another type which is stable over another temperature range. Such metals are said to be *allotropic.* These different lattice forms are, of course, identical by chemical analysis, but they usually possess widely different physical properties.

Iron is the most familiar example of an allotropic metal. In Table 1.2 it is listed as having a body-centered cubic unit cell. This type of structure is retained up to 910 C, but above that temperature the iron changes to a face-centered cubic type. This structure changes in turn to the body-centered cubic type at 1400 C.

The unit cell of the body-centered cubic structure has an atom in each corner of a cube, and one in the center as illustrated in Fig. 1.3a. The atoms should not be pictured as concentrated at these positions, but rather as having their centers of activity located there, and their

electron clouds packed close together, as illustrated by the model made from Ping-pong balls (Fig. 1.3*b*).

The unit cell of the face-centered cubic structure has an atom located in the center of each face, as well as one in each corner of a cube, but none at the center. This arrangement and the corresponding Ping-pong ball model are illustrated in Fig. 1.4*a* and *b*.

The hexagonal close-packed structure is illustrated by the Ping-pong ball model in Fig. 1.5*b*. The unit cell of the space lattice is
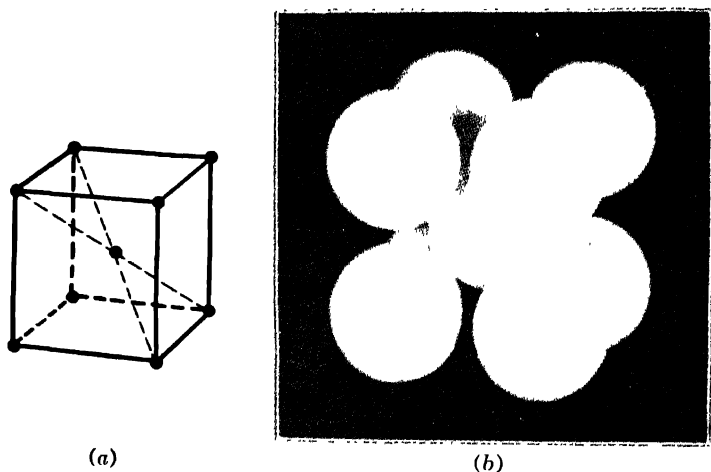

(*a*)   (*b*)

FIG. 1.3. Unit cell of the body-centered cubic structure. (*a*) Sketch showing location of atom centers. (*b*) Pingpong ball model.

simple hexagonal, as shown in Fig. 1.5*a*, and a pair of atoms (a corner atom and an atom within the hexagon) are associated (or clustered) with each lattice point.

The hexagonal close-packed structure and the face-centered cubic structure are closely related. They represent the closest packing of spheres, with each atom having twelve near neighbors. The body-centered cubic has eight near neighbors for each atom, and is a less densely packed structure.

The unit cells may be considered as the effective building blocks of which solid metal is built, much the same as bricks are the building blocks of which walls are built. In the solid metal each atom is shared by the neighboring unit cells. In a cubic lattice, for example, eight neighboring cells share a corner atom. The unit-cell size is characteristic of the metal and very small (e.g., 3.6×10^{-8} cm on an

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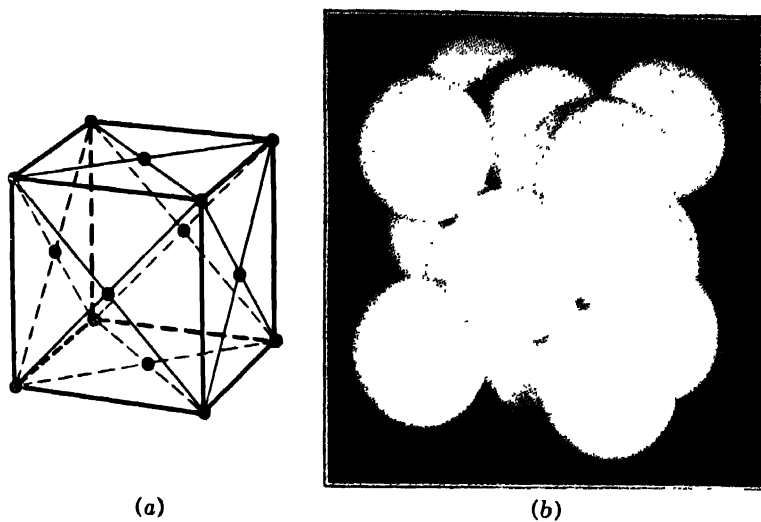</table>

FIG. 1.4.   Unit cell of the face-centered cubic structure. (a) Sketch showing
location of atom centers. (b) Pingpong ball model.

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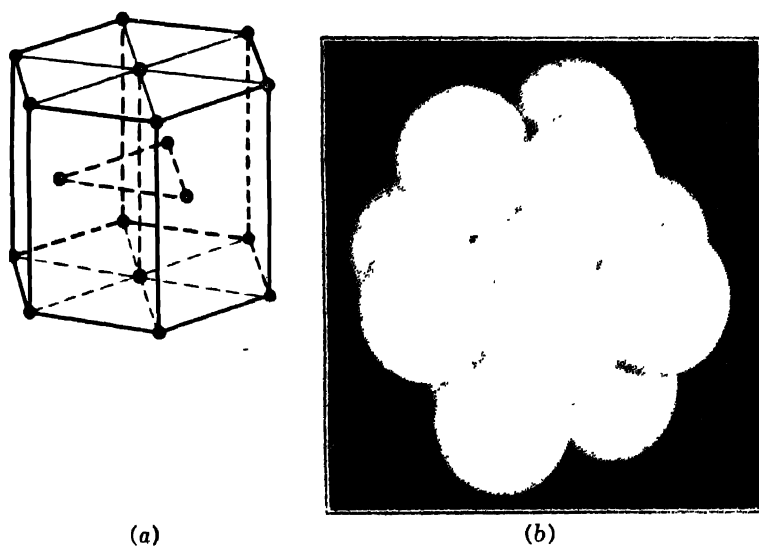<tr><td>(a)</td><td>(b)</td></tr>
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FIG. 1.5.   Unit cell of the close-packed hexagonal structure. (a) Sketch show-
ing location of atom centers. (b) Pingpong ball model with top hexagonal
plane removed and an extra cluster of 3 center atoms below.

edge for copper and 4.078×10^{-8} cm for silver). A *crystal* of metal normally contains many, even millions, of unit cells located side by side and extending in all directions.

1.8 GRAIN FORMATION

At some temperature within a liquid metal the forces of attraction between atoms equal the forces of repulsion, and atoms come together to form a solid nucleus. For this nucleus to remain stable and not
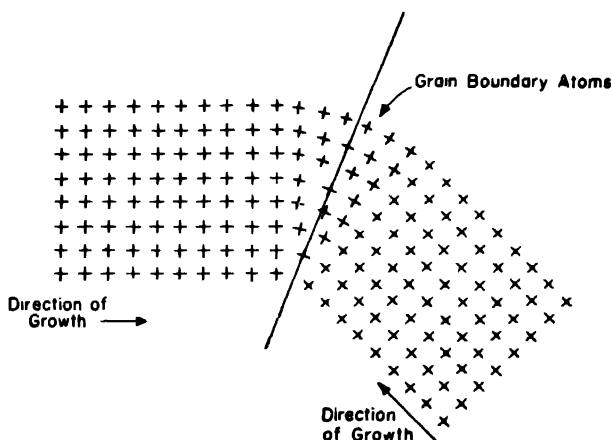

Fig. 1.6. Schematic diagram of the arrangement of atoms at a grain boundary. The crosses indicate atom positions.

redissolve, the latent kinetic energy given up by the atoms must equal or exceed the work done in forming the nucleus. This requires that the nucleus achieve a critical size in order for it to continue to grow. If no other nuclei form, the single nucleus will grow continuously, as atoms of the liquid metal attach themselves to it, gradually building up the space lattice of a single crystal, in which all the atomic planes are parallel. Such single crystals have been produced as large as several inches in diameter and a foot long.

With the usual rate of cooling, however, the solidified metal is generally composed of thousands of crystals, each different in orientation from its neighbors. Each of these crystals started from its own nucleus and grew until it met its neighbors, which were, of course, growing simultaneously from other nuclei.

When two adjacent crystals (more commonly called *grains* in metals) grow together during freezing, the atoms of the last liquid to solidify are mutually attracted to both grains. Since the orienta-

tions of the two grains differ (otherwise they would unite and become one), these atoms cannot form on either lattice, but must occupy compromise positions, as illustrated in Fig. 1.6. This transition zone between grains is called the *grain boundary*. Grain boundaries interrupt the continuity of the lattice planes and increase the resistance of the metal to cold deformation.

The number of grains that form depends jointly on the rate at which the nuclei form and on their rate of growth. For most metals the rate of *grain growth* is low enough so that the rate of nucleation has a predominant influence on the grain size. Since the amount of supercooling determines the minimum size of nuclei that are stable, rapid cooling usually results in the formation of many small grains, and slow cooling produces fewer but larger grains.

1.9 GRAIN STRUCTURES IN CASTINGS

Metals are refined from their ores commercially in three ways. They are (*a*) furnace reduction involving chemical action, (*b*) furnace reduction involving condensation, and (*c*) electrolytic deposition from ore partially refined by furnace reduction.

These refined metals are then put into form for their use by (*a*) pressing and sintering powders or (*b*) by casting from the liquid state into a suitable solid shape.

Most of the tonnage of metal produced today is refined by furnace reduction involving chemical action and then cast. Some is cast into the final form in which it will be used, such as sand, die, or plaster-of-Paris castings. Pure metals are very rarely used as cast shapes, however. More frequently, pure metals are cast into ingots which are later forged, drawn, extruded, or hammered into various shapes such as large cylinders, thin sheets, plates, rods, bars, rails, and wire. But with either ingots or cast shapes, the casting operation introduces two grain structures peculiar to the process. These are described below.

Columnar Grains. In the discussion of grain formation it was assumed that heat was removed uniformly from all the molten metal. Nuclei were then formed throughout the melt; no special grain alignment was noticed; the grains tended to be of the same size and were equiaxed (i.e., of nearly equal dimensions in all directions).

The entire melt in a casting is not cooled uniformly, because the heat is removed through the wall of the container or mold. This causes the metal in contact with the wall to freeze first, and solidification proceeds toward the center from nuclei formed in the vicinity of the walls.

Grains grown from nuclei along the wall intersect neighboring grains, and their size in this direction normally is small. The growth toward the center of the liquid is less restricted by intersection with other grains, because the removal of heat energy through the solid metal at the wall causes limited nucleation in the liquid. As a result,
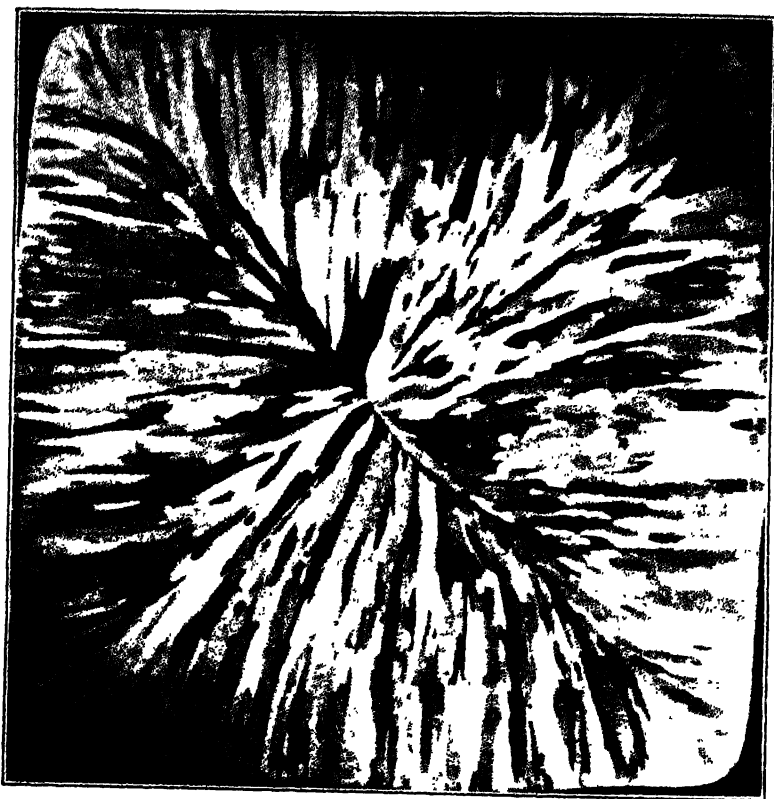

Fig. 17. Photograph of the cross section of a copper ingot showing columnar grains (full size).

when freezing is complete, the grains are very long in directions perpendicular to the walls of the container. Grains of this type are called *columnar grains*. Their occurrence is most pronounced in chilled, thick sections.

Columnar grain growth is particularly undesirable in ingots that have square corners, because planes of weakness are established at the intersections of the columnar grains. These planes nearly bisect the corner angles, as shown in the photograph of the cross section of a

copper ingot (Fig. 1.7), and they reduce the mechanical strength of the ingot, making it susceptible to fracture during working.

Corrugated ingot molds with round corners are used to minimize formation of columnar grains. They cause the grains to grow in all directions. Equiaxed grains will also form and grow if the metal is cooled in such manner that the center reaches a temperature at which nucleation may occur.

Dendrites. A structure known as *dendritic structure,* or *pine-tree structure,* may occur within both equiaxed and columnar grains. It occurs to some degree in most castings because of preferred directional growth. Such growth is a natural characteristic of metals since it is easier to add atoms to the unit cells in certain planes than in others. The more rapid growth in the preferred directions during solidification results in a skeleton crystal formation (a *dendrite*) which contains many interstices filled with melt. These liquid areas freeze last, and their contraction causes regions of microscopic porosity which contribute to somewhat reduced ductility in the cast metal as compared with the same metal treated mechanically and thermally for highest ductility.

The regions of microporosity, which are a result of final solidification of the melt, outline the pine-tree formation of the dendrite. Dendrites are similarly outlined by insoluble impurities or by other structural constituents in alloys,* and this is known as *dendritic segregation.*†

Columnar growth and dendrite formation can be modified in casting shapes or ingots by choice of mold shape and control of grain size. The degree of occurrence of columnar grains and dendrites in alloy castings, however, is largely a function of composition of the alloy. Alloying and casting technique therefore render these effects subject to control.

1.10 PLASTIC DEFORMATION

External loads are applied to metals during many types of processing operations and during service of a product. Such loads may cause two kinds of deformation; elastic and plastic.

Elastic deformation occurs with the application of all loads and is recoverable as the load is removed.

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* Alloys contain a metallic element and one or more other elements. See Chapter 2.

† Dendritic segregation is illustrated in **Fig. 2.13, Chapter 2.**

Plastic deformation is caused by loads greater than the limit of elasticity of the metal. Removal of the load after plastic deformation will allow recovery of the superposed elastic deformation, but the plastic deformation is retained. The shape is changed and changes are caused in the structure and properties of the metal.

The space lattice of each grain of the metal may be reoriented during plastic deformation by rotation, distortion, or both. There are

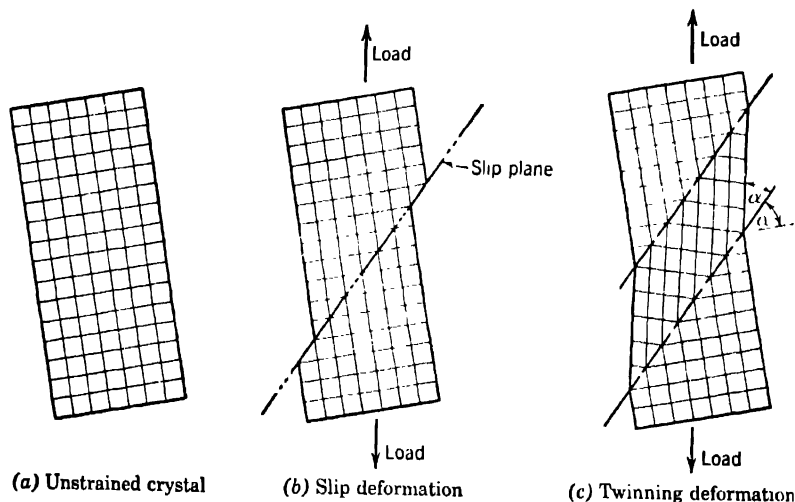(a) Unstrained crystal   (b) Slip deformation   (c) Twinning deformation

Fig. 1.8.   Diagrammatic representation of slip and twinning in a single crystal

three mechanisms by which the deformation takes place; slip, twinning, and formation of deformation bands.

Slip deformation occurs by translation of two parts of a grain, much as occurs in a deck of cards distorted into a parallelopiped. The region between slip planes extends over many atomic distances within which the lattice is distorted   There are several combinations of planes of atoms and directions of slip that can function in a crystal, but the most favorable planes are those that contain the greatest number of atoms and are most widely spaced. The slip takes place along these planes of dense atomic population, even though they may not be aligned with the direction of loading, as shown in Fig. 1.8b. A photomicrograph * of a metal whose deformation has taken place by slip will show many slip lines or bands on the surface of each grain,

* See Chapter 3.

each resulting from a displacement of the type illustrated in Fig. 1.8*b* (see Fig. 1.9*a*).

In *twinning* deformation, a thin platelike section, or lamella, of a crystal changes lattice orientation with respect to the rest of the crystal. The lattice within the twinned portion becomes a mirror image of the rest of the crystal, as would be obtained by rotating this portion 180°. The process of twinning is not one of rotation, however,

FIG. 1.9*a* Photomicrograph of pure iron with a slight amount of cold work. Note the slip lines on each grain. Approximately ×100 (*Rosenhain*).

but occurs by shearing movements of atomic planes over one another. The movement involved does not occur over a multiple of interatomic distances, as does slip. Instead, the near-neighbor relationship of the atoms is maintained. The formation of twins takes place with an audible click. A rapid succession of such clicks is responsible for the "cry" that is heard when a bar of tin is bent. Twinning is a major mechanism in the deformation of zinc, and it is believed that bismuth and antimony deform entirely by twinning at room temperature.

Deformation bands consist of lamellar regions of a grain, within which portions of the lattice rotate in different directions as a result of slip on different planes. The photomicrograph of 70 per cent copper, 30 per cent zinc brass (Fig. 1.9*b*), contains many of these bands.

They appear as shaded stripes across the surfaces of the individual grains.

Although these three mechanisms * define the types of structural changes that occur during plastic deformation, there is much to be learned about the exact nature of the process in different metals. Whatever their nature, the structural changes produce changes in

Fig. 1.9b.   Photomicrograph of annealed 70 per cent copper, 30 per cent zinc brass showing deformation bands or stripes across the surfaces of the grains (×75).

properties. The electrode potential and cohesive force are increased, and the coefficient of thermal expansion and compressibility are slightly increased, whereas ductility is decreased, and a slight decrease occurs in density, electrical conductivity, and maximum per-

* The three types of deformation may be identified in the laboratory by subjecting a sample of polished metal to cold work. Subsequent etching and examination will show lines or bands on the surface, as in Figs. 1.9a and b. If these are removed by repolishing and re-etching, the deformation has occurred by slip. If they persist after repolishing and re-etching, the specimen is subjected to some additional cold work while under examination. The mechanism is then identified by determining whether the deformation lines or bands grow. A deformation band will increase in width under prolonged stress, whereas a twin appears suddenly and does not grow.

meability. Such changes are of considerable importance to metals engineering. Two of them are further discussed in the following sections.

1.11 STRAIN HARDENING

Atomic planes, which are suitably oriented, slip quite readily as a load sufficient to cause plastic deformation is first applied. Slip generated on these planes progresses to the grain boundaries or to other imperfections, where a stress field is set up that tends to oppose additional slip. Further slip must then take place in grains with less favorably oriented slip planes, and additional load is required to orient these grains so that their slip planes may be utilized. Thus, as the deformation proceeds, the availability of slip planes decreases, and the tendency to resist deformation increases. When the resistance of a metal to deformation has been increased in this way, the metal is said to be *strain hardened,* or *work hardened.*

The process may be likened to the suspension of a weight load by a chain. The weakest chain link breaks first as the load is increased. If this link is removed, thereafter the chain can withstand larger and larger loads as each succeeding weak link breaks and is removed. Of course, the deformed grains do not break nor are they removed, but they are supported sufficiently after deformation, so that further slip, in turn, takes place in other grains.

Strain hardening is utilized in processing many metals to provide strength and hardness greater than the metal possesses in the as-cast condition.

1.12 PREFERRED ORIENTATION

Preferred orientation is said to occur within a metal when certain lattice directions in the grains are aligned with the principal directions of flow under severe deformation (see Fig. 1.10). The progress of this alignment is slow as deformation proceeds. Its nature and the manner in which it is accomplished are characteristics of the metal and the type of deformation.

The tendency to align the crystalline lattices may result in directional properties, since such properties as strength and magnetic permeability of the crystals of some metals differ in various crystalline directions. Sometimes these directional properties are valuable, as with increased magnetic permeability in the direction of flow for transformer laminations; and sometimes harmful, as for strip in which bends are to be made parallel to the direction of flow.

Fig. 1 10. Photomicrograph of copper cold worked to one-half original size.
Note tendency for grain alignment in the horizontal direction (×250).

1.13 COLD WORKING

Rolling, forging, drawing, and extrusion are typical methods by which metals are worked. The metals furnished in the shapes resulting from these operations are known broadly as *wrought* metals.

Cold working refers to the act of permanently deforming a "cold" metal. The term "cold" is relative. Even room temperature may be "hot" for metals such as lead, as will be explained in paragraph 1.14 on recrystallization.

Since a metal section is deformed plastically when it is cold worked, strain hardening and directional properties are produced in the deformed regions. The degree of each depends on the characteristics of the metal worked and the flow induced by the working operation. Rolling, for example, produces more deformation, strain hardening, and directional properties at the surfaces of a sheet or strip than in the center.

If cold working is severe enough, the metal will fracture. Fractures resulting from cold deformation are transcrystalline; that is, through the grain. They indicate that failure occurs when lattice

distortion progresses to the point at which cohesion between atoms is finally exceeded.

The cold-working process is of considerable value in industrial fabrication. It often offers economic advantages in forming basic shapes or finished parts. And it frequently reduces material and size requirements because of the beneficial effects of strain hardening and directional properties. Stresses left by the working operation, however, may prove harmful if not relieved, since they increase susceptibility to corrosion, raise notch sensitivity, may decrease fatigue resistance, and cause dimensional changes during machining.

1.14   RECOVERY, RECRYSTALLIZATION, AND GRAIN GROWTH

A work-hardened metal is in a state of unsatisfied equilibrium as a result of residual stresses and the natural tendency to return to a symmetrical lattice. If the temperature is raised sufficiently, the metal attempts to approach equilibrium through three processes: recovery, recrystallization, and grain growth.

Recovery. In this process a change occurs in those properties associated with the internal stress of a cold-worked metal. The heating applied tends to realign the atoms in their lattice but does not cause detectable change in the grain outline. As a result, the internal stresses are relieved in the cold-worked metal without reduction of the mechanical strength (see Fig. 1.11).

Recrystallization. This region derives its name from the process which occurs with heating in excess of that used for recovery. New grains are formed, and thus the metal is said to recrystallize.

There is a tendency for metals to form equiaxed grains during recrystallization, but the preferred orientation resulting from the working operations is retained to some extent. Present-day theories on the manner in which some of the preferred orientation is retained are still inadequate. However, it is known that the degree of retention is affected by the temperature utilized for recrystallization, purity of the metal, degree of previous cold work, and the starting structure.

Three main factors control the recrystallization process for a particular metal. They are temperature, time at temperature, and the amount of previous cold work. The temperature required is reduced by increased heating time. The required temperature is also reduced by increased amounts of previous cold work. Other factors that reduce the required temperature for recrystallization are smaller grain size prior to cold work, lower temperatures during cold work, and greater purity in the metal.

Only a short time, such as 1 or 2 hr, can be allowed in practice for the recrystallization process to take place after the metal has been heated to the necessary temperature. The lowest temperature of re-
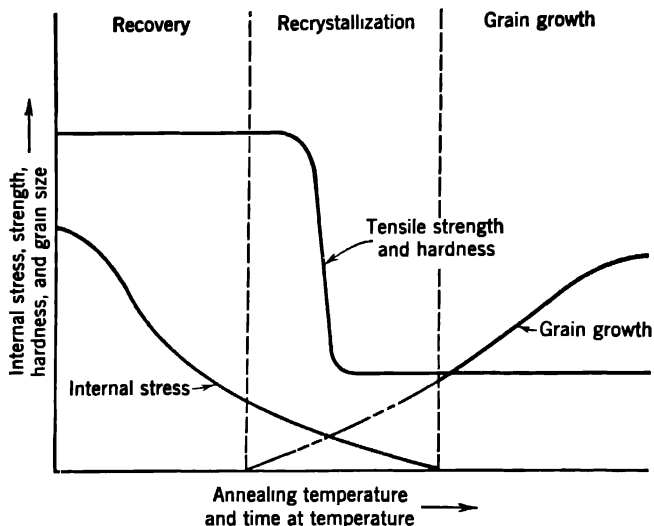

FIG. 1.11. Effect of heating on a cold-worked metal.

crystallization for this "heating time" is given for some common pure metals in Table 1.3.

Table 1.3 Practical Short-Time Temperature of Recrystallization for Some Common Pure Metals

Tungsten	1200 C	Silver	200 C
Tantalum	1000 C	Aluminum	150 C
Molybdenum	900 C	Magnesium	150 C
Nickel	600 C	Zinc	Room temperature
Iron	450 C	Cadmium	About room temperature
Platinum	450 C	Tin	About room temperature
Copper	200 C	Lead	Below room temperature
Gold	200 C		

The formation of new grains in recrystallization causes further relief of internal stress, reduction in mechanical strength and in hardness, and recovery of the ability to withstand plastic deformation. This last effect is of particular importance to industry since it permits additional working, e.g., deep drawing, to be performed on a

metal which had in a previous operation become too hard to work and liable to fracture with further work.

The formation of new grains is also of importance in refining coarse and segregated grain structure in cast ingots of pure metal. The ingots must, of course, be cold worked before they will recrystallize.

Grain Growth. Just after a metal has recrystallized, the grains are small and somewhat regular in shape. The grains will grow if the temperature is high enough or if the time at temperature is allowed to exceed the minimum required for recrystallization. This growth is the result of a tendency to return to a more stable and larger state, and appears to depend primarily on the shape of the grain.

The mechanism by which this growth occurs is thought to be as follows. The atoms in the grain boundaries are in a high-energy state. When the metal is heated to a high enough temperature, these atoms have enough mobility to align themselves with a crystal lattice. Because of the tendency to return to the most stable (low-energy) state, they line up with the larger grain. Atoms from the adjacent grain then take up boundary positions and proceed similarly. The resulting change from one grain to another may be thought of as movement of the boundary zone into the smaller grain, thus making the small grain smaller and the large grain larger. The process continues until the small grain is absorbed by the large grain.

For any temperature above the recrystallization temperature, normally there is a "practical maximum size" at which the grains will reach "equilibrium" and cease to grow appreciably, no matter how long they are held at temperature. There are, however, certain kinds of abnormal grain growth that occur as a result of applied or residual gradients of strain due to nonuniform impurity distribution, and which permit growing very large single grains.

The grain structure of a pure metal which has no allotropic transformation, e.g., copper, cannot be refined without first cold working the metal. Even then, the metal must be heated to the recrystallization temperature or above, and heating must be discontinued before excessive grain growth occurs. Merely heating a pure metal that contains no plastic strain and is not allotropic will cause grain growth, and not recrystallization.

1.15 HOT WORKING

Hot working is done in the same manner as cold working except at a temperature high enough to produce recrystallization simultane-

ously with the deformation. Thus, the metal is recrystallized during hot working before it can effectively strain harden.

The lattice layers of the grains can more easily slip over each other at recrystallization temperatures. As a result, additional slip planes are available and the metal has greater deformability or "plasticity." This characteristic is the chief reason for working metals in the "hot" condition. Economic and efficient shaping result.

Although refinement of grain by simultaneous recrystallization is usually only a secondary objective of hot working, it is important. The hot-working schedule should be carried out in such a way that the metal cools to the recrystallization temperature at about the same time that the plastic working is finished, so that the minimum grain size will result. If working is stopped at too high a temperature, grain growth will occur during cooling, thus tending to nullify the refining effect of the hot work. If, on the other hand, working is carried on too long and the metal cools below the recrystallization temperature, cold working would be effected.

The term "hot working" may apply to some operations where there is no heat applied at all. For instance, room temperature is at or above the recrystallization temperature for lead, tin, and zinc (see Table 1.3) and these metals can be "hot worked" without the addition of heat. Tungsten by comparison can be "cold worked" at a temperature of 1000 C, which is still below its recrystallization temperature.

If a metal is fractured during hot working or under short-time service loading at a temperature well above that for recrystallization, the fracture will not occur across the grain as for cold-work fractures. Instead, it will follow the grain boundaries, i.e., it is "intergranular." This indicates that the grain boundaries are weaker than the grains at hot-working temperatures, and the metal fails when the applied stress exceeds the cohesion between atoms in the grain boundary.

1.16 CREEP

Metals will deform under steady service loads less than the short-time elastic strength if the loads are applied for a very long time at temperatures near the recrystallization temperature. Apparently, the atoms tend to flow in the direction of the load and, with substantial stresses, high temperatures, and sufficient time, the deformation becomes significant. Greater stress, temperature, and time will actually produce fracture.

This phenomenon is known as *creep*. It is especially important in turbine and other highly-stressed, high-temperature devices which must operate for a long time. The creep of metals is discussed in more detail in Chapter 4.

1.17 CONCLUSION

The description of pure metals in this chapter has been based on the most up-to-date theories in the science of metallurgy. All theories, however, are valid only so long as they explain observed phenomena in a satisfactory manner. It can be expected in the future that more satisfying explanations of some phenomena will be devised as more information is obtained on the nature of atomic structure. Meanwhile, the existing theory forms an adequate working tool.

The engineer is cautioned that emphasis has been placed on those phenomena that are of particular interest and value to him in his work. There is, of course, a great deal more in the fundamental science of metallurgy. The metallurgist should be consulted when specific problems appear beyond the scope of this presentation.

Review Questions

1. What is the difference between the field of process metallurgy and that of physical metallurgy?

2. Explain what is meant by the "triple point" for a metal.

3. What characteristic of atomic structure of metals accounts for their relatively high thermal and electrical conductivity?

4. What is the crystal lattice of a solid metal, and what part of the lattice is called a unit cell?

5. Describe how separate grains are formed when a metal is solidified.

6. What two characteristics of the metal determine the number of grains that will form?

7. Iron is said to have several allotropic forms, e.g., alpha, gamma, and delta iron. What takes place in the iron when it changes from one allotropic form to another? How can this allotropic change be produced?

8. Explain how columnar growth and dendritic segregation can occur.

9. What are wrought metals?

10. Name the temperature that distinguishes hot working from cold working.

11. Name the three mechanisms by which plastic deformation may occur in metals.

12. A broken piece of metal was microscopically examined and the fracture was found to follow the grain boundaries. What would be the most probable type of service conditions for this piece of metal?

13. One strip of annealed metal is reduced by cold work from $\frac{1}{4}$ in. to $\frac{1}{8}$ in. in thickness, and another strip of the same metal is reduced from $\frac{1}{4}$ in. to $\frac{3}{16}$

in.   Which one would recrystallize at the lower temperature and which one would have the higher strength?

14. What two factors must be controlled if grain growth is to be limited when full annealing a piece of metal?

15. What operation must be used in conjunction with heat treatment to refine the grain size of a pure metal that has no allotropism?

2 ALLOYS

2.1 INTRODUCTION

A substance that possesses metallic properties and is composed of two or more elements, of which at least one is a metal, is called an *alloy*. The metal present in the alloy in largest proportion is called the *base metal*. All other elements present, either metallic or non-metallic, are called *alloying elements*.

In industry, the elements designated as alloying elements are those added *intentionally* to secure certain desirable properties. These elements are distinguished from elements called *impurities*, which are present more or less accidentally. Usually, impurities are present because it is technically impossible or uneconomical to eliminate them. They may originate in the ore, and they may result from contamination introduced during refining, melting, or casting. Sometimes they may actually be added in minute quantities to promote solidification or to counteract the effect of other impurities.

Alloying elements, either in minute quantities or in significant quantities, may result in a marked change in the properties of the base metal. For instance, an alloying element may change the re-crystallization temperature of a metal and its corrosion resistance, electrical conductivity, or magnetic permeability. It may cause an increase or decrease in the degree to which hardening occurs under cold working. A very important characteristic that may be imparted by alloying is to make possible an increase in strength and hardness by heat treatments alone. Alloys are, therefore, of importance to industry in providing materials with properties that pure metals alone do not possess.

The structure resulting from addition of alloying elements to a base metal determines the properties of the alloy. The purpose of this chapter is to discuss the internal structures characteristic of alloys and to describe the effect of these structures on properties.

2.2 ATOMIC ARRANGEMENT IN ALLOYING

The crystal structure of a pure metal consists wholly of one characteristic lattice arrangement over a given temperature range, as described in Chapter 1. The crystal structure in alloys is complicated by the presence of the alloying elements, which may exist together with the base-metal atoms in three general ways.

(1) Alloying atoms may be relatively *insoluble* in base-metal atoms.

(2) Alloying atoms may be relatively *soluble* in base-metal atoms.

(3) Alloying atoms may form a *compound* with base-metal atoms.

A particular alloy may consist wholly of one of these arrangements or of a combination of them.

2.3 INSOLUBLE MIXTURES

When the alloying atoms and the base-metal atoms are relatively insoluble in the solid state, each exists almost independently in an intimate mixture of grains. Grains of each element retain their own identity, space lattice, and properties.

Impurities retained from the ore or from processing, when insoluble in the base-metal atoms, are called *inclusions*. They are usually oxides, sulfides, silicates, and similar compounds. If the impurities are gaseous they may produce *porosity*.* Both inclusions and porosity constitute defects in the base-metal structure, with consequent reductions in mechanical properties.

2.4 SOLID SOLUTIONS

Alloys containing alloying elements that are relatively soluble in the base metal in the solid state are termed *solid solutions*. They are the most common form of alloying.

The solid solution is termed *substitutional* when the alloying atoms replace base-metal atoms in the space lattice of the latter. That is, the solution of alloying atoms occurs by substitution of these foreign atoms in the base-metal lattice structure. The substitution is not necessarily identical in each unit cell, but is statistically uniform over the entire grain. The lattice size of the solid solution will differ from that of the base metal if the alloying atoms in solution (called *solute* atoms) are larger or smaller than the host atoms (called *solvent*

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* Some degree of porosity also results from imperfections in lattice formation in pure metals and alloys.

atoms). Monel metal is an example of a substitutional solid solution in which copper is dissolved in nickel. Its photomicrograph, Fig. 2.1, illustrates that the grains etch uniformly, similar to a pure metal.

Solubility is a matter of degree. It is influenced primarily by: (1) size of solute atoms in relation to size of solvent atoms, (2) chemical affinity of the elements for each other, and (3) the relative valency effect. Complete solubility in all proportions usually takes place with atoms having less than 14 or 15 per cent difference in atomic diameter. Higher differences cause limited solubility. The tendency to form chemical compounds also limits solubility. The mechanism of solid solubility remains the same, however, whether the atoms are soluble in all or limited proportions. This is analogous to comparison of alcohol-water liquid solutions with salt-water liquid solutions. Alcohol and water are soluble in each other in all proportions. The solution of salt in water is limited and only a fixed percentage may be dissolved depending on pressure and temperature. If greater percentages of salt than the limit are introduced, the excess will not dissolve, and both salt and salt solution will be present. In solid alloys of limited solubility, having excess alloying atoms, some will be in solution with the base-metal lattice, and the excess will be present as grains of its own structure or as a compound with the base metal.

FIG. 2.1. Photomicrograph of monel metal (67 per cent Ni, 30 Cu, 3 Fe, Mn, and impurities). Dark lines outline grains that etch uniformly. Impurities show as black dots ($\times$250).

A random substitution of solute atoms in the base-metal lattice is usual for solid solutions. In some rather rare cases, however, a rearrangement of atoms will take place under slow cooling or annealing at low temperature, and the solute atoms will take definite and periodic positions in the base-metal lattice. Such ordered lattices are termed *superlattices*. Although they are extremely temperature sensitive, they are stable otherwise, and the ordering is accompanied by

change in mechanical and electrical properties. Alloys of copper and gold possess the ability to form superlattices, either as $AuCu_3$, with gold on the corners and copper on the faces of the face-cubic structure, or as AuCu in the tetragonal structure (see Fig. 2.2).

(a) Ordered $AuCu_3$ (b) Disordered $AuCu_3$ (c) Ordered AuCu

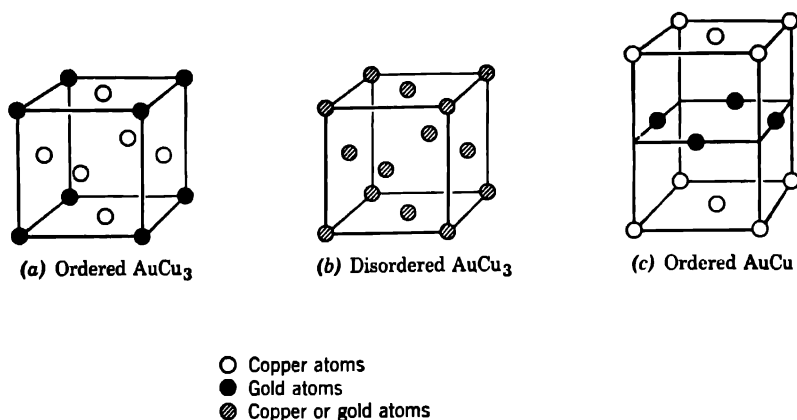○ Copper atoms
● Gold atoms
◉ Copper or gold atoms

Fig. 2.2. Ordering in gold-copper alloys. (a) Unit cell of face-centered $AuCu_3$, showing ordering with copper on faces and gold at corners of lattice. (b) Disordered space lattice with gold or copper at atom locations of face-centered cubic; proportions are 25 per cent gold and 75 per cent copper. (c) Unit cell of tetragonal ordered AuCu.

Another form of solid solution involves random location of solute atoms in the spaces between the host atoms. This type solid solution is termed *interstitial*. It has higher density than the substitutional type and usually takes place with solute atoms which are much smaller than those of the base metal, causing some enlargement of the host-metal lattice. An example of this type is a solid solution of carbon in iron. The other elements that form interstitial solid solutions are H_2, N_2 and B.

2.5 INTERMETALLIC COMPOUNDS

Some alloys containing at least two metals possess the ability to form, upon solidification, an ordered lattice corresponding to simple whole-number ratios of the combining metallic elements; e.g., a_1b_1, a_2b_3, etc. Such ordered lattices are known as *intermetallic compounds*.* Their lattice form is characteristic of the compound, it

* They are also termed an intermediate phase, a phase which is not continuous with one of the pure metals of the system. Classification of an intermediate phase as an intermetallic compound is justified only if there is a narrow range

differs from those of its components, and usually is more complex.

The lower order of symmetry in the complex lattices results in low electrical conductivity and greater resistance to slip. Consequently such compounds are both hard and brittle. Particles of them properly dispersed throughout a softer base metal will strengthen the latter. There are many intermetallic compounds that are of importance for this effect. Two examples are cementite, Fe_3C, which contributes to the hardening and strengthening of steel, and copper aluminide, $CuAl_2$, which hardens certain aluminum base alloys.

2.6   ALLOY PHASES

It is evident from previous paragraphs that a solid alloy may consist of grain mixtures, solid solutions, or intermetallic compounds of its elements. Each of these, if present, could be detected by proper analysis. Each is considered metallurgically as a different phase.

A *phase* is defined as a portion of matter which is homogeneous in the sense that its smallest adjacent parts are indistinguishable from one another. Since all vapors are miscible, there can be only one vapor phase for an alloy. But there may be several liquid and solid phases. For example, solid copper is a phase, liquid copper is a separate phase, and a solid solution of copper in nickel is still another phase. A mechanical mixture of lead and copper constitutes two phases. Each phase has its own atomic arrangement, physical properties, and chemical properties. A phase change, accordingly, is accompanied by a change in properties.

The number of phases that may be present in a given alloy, at a given temperature and pressure, is predictable if the alloy is in equilibrium with its environment at the temperature and pressure. In this condition the alloy has no further tendency to change, however long a time may elapse. Equilibrium is considered a dynamic condition of balance between atomic movements where the resultant is zero. The condition is one of rest rather than change. This implies absence of strain from cold working or thermal treatments; consequently, the rates of heating and cooling that may be permitted on a given alloy, during which equilibrium may still be retained, are limited. The condition of equilibrium is often achieved, however, in mechanically worked and "dead" annealed products such as wire, sheets, forgings, pressings, and rolled shapes.

of homogeneity, simple atom proportions, and atoms of identical kind occupy identical points throughout the space lattice. Intermediate phases often occur over a broad range of concentration, however.

The general law that prescribes the number of phases present at equilibrium conditions is known as *Gibb's phase rule*. It may be expressed by the equation

$$P = C + 2 - F$$

where P = number of phases present, C = number of components, and F = degrees of freedom. The number of components is the minimum number of spieces needed to express quantitatively the composition of all phases present. In metals the number of components corresponds to the number of elements comprising the alloy system. The number of degrees of freedom indicate the number of independent variables (temperature, pressure, and concentration) that may be varied without altering the number of phases. In an alloy containing two elements, $C = 2$. For this alloy, $P = 4$ when $F = 0$; $P = 3$ when $F = 1$; and $P = 2$ when $F = 2$. Thus, four phases may be present when temperature, pressure, and concentration are fixed. Three phases may be present when, with pressure fixed, temperature and concentration are varied together (1° of freedom). Only two phases may be present when, with pressure fixed, temperature and concentration are varied independently. This rule is the foundation of the constitution diagram described in the next paragraph.

2.7 CONSTITUTION DIAGRAMS

The most comprehensive and satisfactory method of describing the nature and constitution of alloys of a given system is the *constitution diagram*. Since this diagram indicates the relative amount and composition of phases present in an alloy at a given temperature and pressure when the alloy is in equilibrium, it is also known as a *phase diagram* or an *equilibrium diagram*.

Constitution diagrams have been prepared for many alloys containing 2 and 3 elements. These diagrams could also be applied to alloys with more components by plotting the phase compositions for 2 or 3 elements with the others maintained constant. For the sake of simplicity, however, and to keep on ground that has been fairly well explored, only 2-element (called *binary*) systems will be discussed in the following.

The constitution diagram for binary alloys is plotted in two dimensions with temperature as the ordinate and percentage composition as the abscissa, see Fig. 2.3. The left edge is 100 per cent of the element on the left, and the right edge 100 per cent of the element listed on

the right. The intermediate percentages are usually by weight of the 2 elements. The diagram thus covers all possible alloys that can be formed between the 2 elements at a given pressure.

Points are plotted on the diagram from studies of phase changes in prepared alloys. Data on these changes may be obtained by analysis of cooling curves, from measured changes in volume or dimensions with temperature, from analysis of structural changes in specimens heated to different temperatures and quenched, from measured
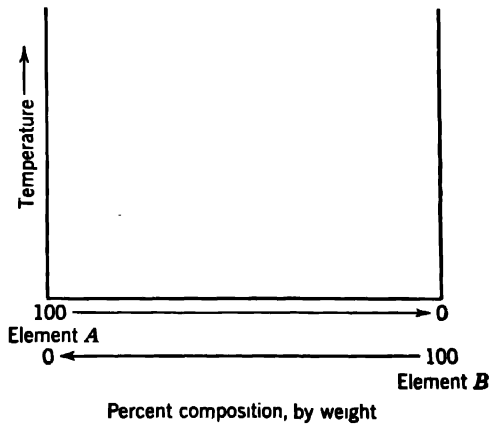

FIG. 2.3. Constitution diagram coordinates for binary alloys.

changes in electrical conductivity, or from X-ray analysis of lattice form. These points are then connected by lines to show the regions in which various structures or phases will exist under equilibrium conditions.

The effect of pressure is usually not plotted on the constitution diagram for solid-solid and solid-liquid equilibrium. Instead, each diagram is plotted for constant pressure, usually atmospheric, since small pressure variations have little effect on equilibrium when the vapor phase is not present. The effect of high pressures has not been extensively studied.

2.8 ALLOY VAPORS

The vapor phase of alloys is usually not included in constitution diagrams because this field has not been of sufficient importance to warrant study. Perhaps developments in methods for creating high temperatures will enhance interest in this aspect of metallurgy, particularly for very high temperature formation of metal compounds.

The vapor pressures of liquid and solid alloys are comparable to those for pure metals. All are very low, and only those of the low-melting-point metals have become of commercial interest. The vapor pressure of an alloy is equal to the sum of the partial pressures of its constituent elements, if the elements are insoluble. Solid solutions and liquid solutions have lower vapor pressures than the sum of the partial pressures of the pure elements at the temperature of comparison (Raoult and Henry's Laws). Compounds of elements tend to have still lower vapor pressures.

2.9 LIQUID ALLOYS

Most alloys are homogeneous when liquid and will mix (be soluble or miscible) in all proportions. The liquid for such alloys is uniform, and the identity of each component is not separately retained. When the components of the alloy are insoluble (immiscible) in the liquid state, the lighter liquid will float above the heavier unless mechanically agitated to form a mixture in which globules of one are dispersed throughout the other. Occasionally, elements will form compounds in the liquid state, and these may behave as either miscible or immiscible liquids with the excess of either constituent. Lines separating miscible from immiscible solutions, and compounds from such solutions are the regions depicted on constitution diagrams in the liquid state. These reactions, too, are of limited interest and are seldom shown because reactions from liquid to solid and in the solid metal are of primary importance.

For simplicity, the processes occurring in solidification will be discussed separately from those processes which occur in solid metal. Reference to each reaction applying to a particular alloy will indicate its final structure and associated properties.

2.10 SOLIDIFICATION OF ALLOYS

Pure metals are known to freeze (solidify) at a constant temperature under near-equilibrium cooling rates. Alloys, by contrast, usually freeze over a range of temperature, and freezing most often begins at a temperature lower than the freezing point of the principal component alone.

Soluble Liquid and Soluble Solid. The constitution diagram in Fig. 2.4 describes an alloy system which is completely soluble in the liquid and solid state. In this alloy the freezing point of only one element is lowered by addition of the other. The freezing point of metal *B* in Fig. 2.4 is shown as that which is lowered by addition of

metal A. The line that denotes the temperatures at which freezing begins is a nearly straight line between the freezing points for the pure components. This line is called the *liquidus*. The line which denotes temperatures at which freezing is complete is called the *solidus*. It falls somewhat below the liquidus. Two phases, liquid solution and solid solution, exist together in the "mushy" range between liquidus and solidus. Below the solidus the alloy consists wholly of a single-phase, solid solution of the components.
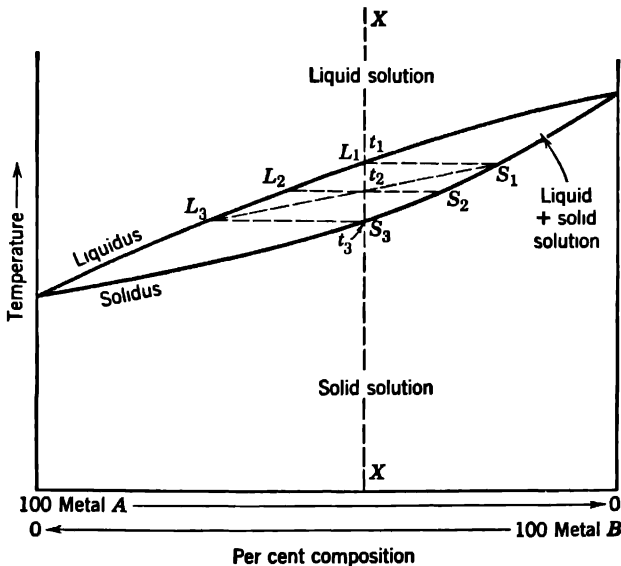

Fig. 2.4. Constitution diagram for a binary-alloy system soluble in both liquid and solid states.

Suppose an alloy of composition x–x, Fig. 2.4, is cooled slowly from the melt so as to approximate equilibrium conditions. At temperature t_1, liquid of composition L_1 is in equilibrium with solid of composition S_1, and solidification of grains of composition S_1 begins by formation and growth of nuclei as described in Chapter 1 for pure metals. After further cooling to temperature t_2, L_2t_2/L_2S_2 of the alloy has solidified and S_2t_2/L_2S_2 of liquid L_2 is in equilibrium with this solid, which has a composition S_2. This method of determining proportions of each phase present is known as the *tie-line concept* and results from a mass balance for the system. At lower temperatures liquid of composition denoted by intersection with the liquidus is similarly in equilibrium with the composition denoted by intersection

with the solidus. At t_3, 0 per cent liquid is in equilibrium with all the solid of composition S_3. Solidification is complete at this temperature for alloy x–x. The solid S_3 is chemically uniform and of the same composition as the original molten alloy x–x, provided free movement of atoms A and B was permitted by the thermal diffusion process, so that equilibrium between all phases could be maintained at all times.

The role of diffusion in obtaining uniform composition may be explained as follows. During the early part of the freezing process the solid precipitated is richer in metal B than the original melt. This leaves the remaining melt richer in metal A, as shown by the shift in composition L_1 to L_3. The composition of liquid added to the solid during each increment of temperature drop thus follows the compositions of some line indicated by the dotted connection between S_1 and L_3. At sufficiently slow cooling rates homogenization of the solid takes place, so that the entire solid becomes of uniform composition. The process by which this occurs is known as *diffusion*. It involves migration of atoms in the solid under the impetus of temperature and the tendency to attain the lowest energy state. Since diffusion similarly occurs in the remaining liquid, its composition, too, is maintained uniform during equilibrium freezing Diffusion is important in alloys since it is a basic process in all structural and phase changes produced by heat treatment.

A common example of a completely soluble alloy system is that of copper and nickel, in which nickel is the higher melting component. Gold-silver, magnesium-cadmium, platinum-copper, platinum-gold, and tungsten-molybdenum alloy systems also are of this type.

Complete Solubility with Maxima or Minima Liquidus. A limiting case of Fig. 2.4 occurs when the liquidus contains a point of inflection, indicating either a maximum melting point, higher than either component, or a minimum melting point, lower than either component. The latter is most common in binary systems showing complete solubility (often called isomorphous systems). The constitution diagram of Fig. 2.5 is typical of this type. Alloy compositions on either side of the minimum point freeze as described for Fig. 2.4. The composition at the minimum point freezes at constant temperature, like a pure metal, with formation of one-phase, completely soluble grains. The reaction is reversible and may be designated $L \rightleftarrows \alpha$, where L denotes liquid, and α denotes a solid solution. Alloys of this type occur in the iron-chromium, chromium-molybdenum, iron-vanadium, gold-copper, gold-nickel, and nickel-platinum systems.

Soluble Liquid, Partially Soluble Solid. A very important alloy is the type that possesses partial solubility in the solid state. Tl.e constitution diagram for this alloy system is illustrated in Fig. 2.6. The liquidus line indicating the temperature at which freezing begins drops steadily with increasing amounts of metal *B* in metal *A*. Similarly, for metal *B* on the right side of the diagram, the liquidus drops with increasing amounts of metal *A*. The two drooping liquidus lines meet at some point *r*. Solidus lines connect with the melting points
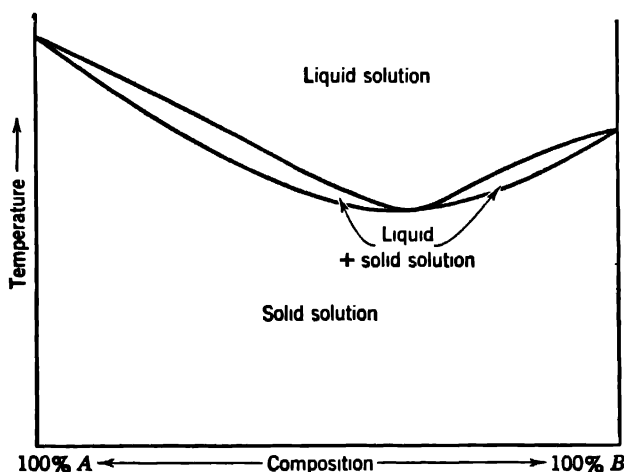

FIG. 2.5. Constitution diagram for complete solubility with a minimum liquidus.

of the pure metal *A* and *B*, and fall somewhat below the liquidus as for the alloy systems previously described. There is a major difference, however, in their junction at *p* and *s* with a horizontal line through the liquidus intersection at *r*.

An alloy richer in *A* than point *p* freezes, as described for completely soluble alloys, Fig. 2.4, to form uniform grains of a solid solution of metal *B* in metal *A*. This solid solution is denoted alpha, *α*, to differentiate it from pure metal *A*. Alloys richer in *B* than point *s* freeze similarly, forming uniform grains of a solid solution of metal *A* in metal *B*. This solid solution is denoted beta, *β*, to differentiate it from pure metal *B*.

The alloy of composition at *r* freezes at constant temperature as does a pure metal. It also has the lowest freezing point of any alloy of the system, hence it is designated an *eutectic* alloy, from the Greek meaning "most fusible." The point *r* is therefore called the eutectic

point, and the corresponding temperature is called the eutectic temperature. Since solid alloys of compositions between p and s consist of two phases, α and β, the eutectic alloy transforms from liquid to two solid phases upon freezing. This reaction, called the *eutectic reaction*, is reversible and is denoted $L \rightleftarrows \alpha + \beta$. The transformation on freezing causes alternate precipitation of tiny grains of α and β from the liquid until solidification is complete. The precipitation

FIG. 2.6. Constitution diagram for solidification of a binary-alloy system soluble in the liquid state and partly soluble in the solid state.

occurs with α grains next to those of β, since precipitation of one leaves adjacent liquid supersaturated with concentrations of the other, causing its near precipitation. The solidified structure will resemble a "salt and pepper" mixture of α and β, like that of Fig. 2.7, or will form a laminated platelike structure of the two phases, α and β.

During cooling of an alloy of composition x–x, which is between that for points p and r, liquid of composition L_1 is in equilibrium at temperature t_1 with solid solution of B in A having composition S_1, and solidification of α grains begins. They are termed *primary* alpha grains. At temperature t_2, liquid of composition L_2 is in equilibrium with primary grains of S_2. From the tie-line concept, the liquid proportion at this temperature is mn/mo, and the solid is no/mo. Just before t_3 is reached, pq/pr liquid of eutectic composition is in equilibrium with qr/pr solid of composition S_3. Further cooling causes

this remaining liquid to freeze at constant temperature, forming a matrix of eutectic around the primary grains previously formed. The solid of this alloy therefore consists of two phases, α and β, but the structure is made up of primary grains of α surrounded by an eutectic matrix of α and β. The line p–s through point r is therefore an eutectic isotherm indicating that for these compositions the last liquid to freeze will be of eutectic composition.
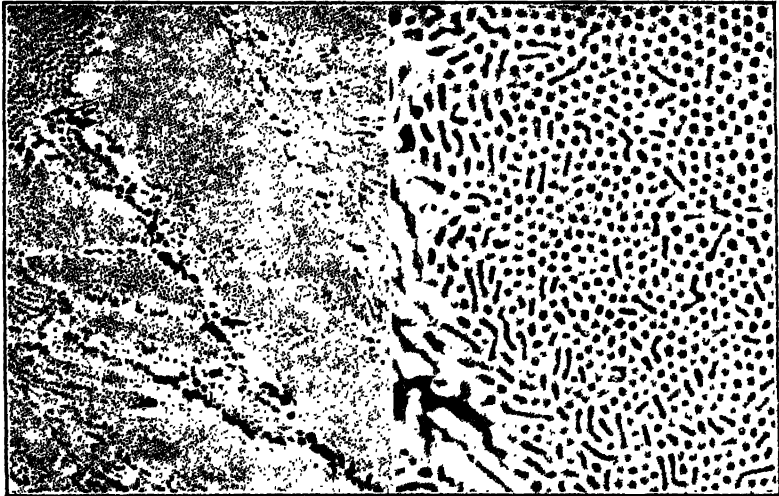

FIG. 2.7   Photomicrographs of iron-carbon eutectic-alloy (4.3 per cent C, balance Fe) specimen cooled very slowly from the melt. Dark phase is pearlite, white phase is cementite, Fe_3C. *Left* $\times 100$. *Right* $\times 500$.

An alloy rich in B will solidify similarly to form primary grains of β surrounded by an eutectic matrix of α and β.

Alloy systems typical of this type are tin-bismuth, tin-lead, lead-antimony, cadmium-zinc, nickel-chromium, and silver-copper. The tendency for limited solubility of B in A is usually not the same as A in B. The less electropositive base metal usually dissolves more of the more electropositive.

When two metals of this type have so little solubility for each other as to be relatively insoluble, the constitution diagram of Fig. 2.6 approaches one of the forms of Fig. 2.8a or b. In Fig. 2.8a the eutectic point remains at intermediate concentrations, but the solubility for one or both metals for the other is very limited. Although solubility may be almost infinitesimal and the solid grains may ap-

proach the properties of the respective pure metals, technically speaking they are actually solid solutions. Silver-lead, aluminum-silicon,
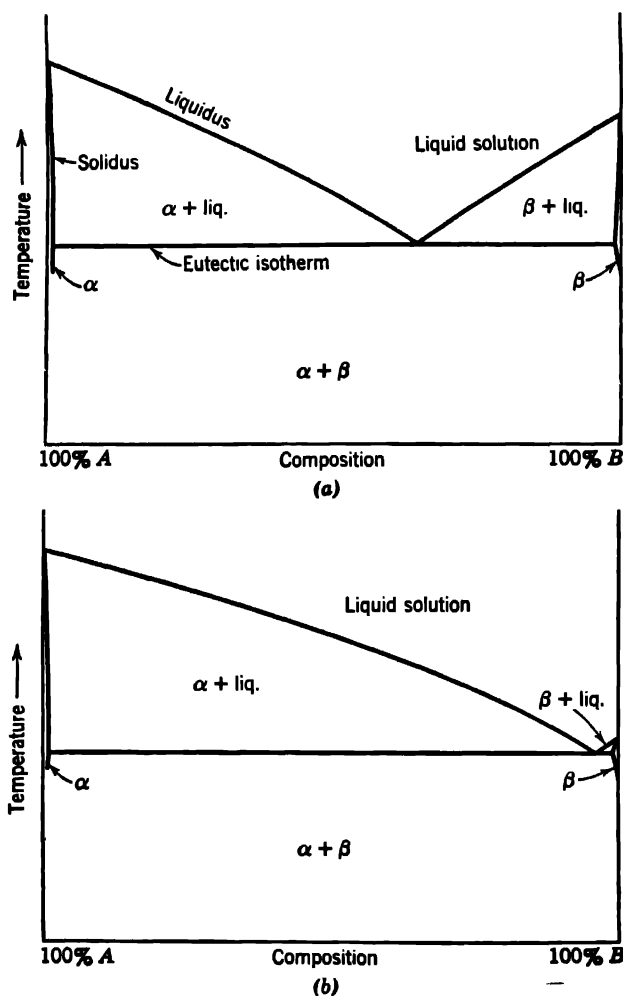

Fig. 2.8. Constitution diagram for two cases of binary-alloy systems soluble in the liquid state and minutely soluble in the solid state. (a) Eutectic temperature at intermediate concentrations. (b) Eutectic temperature near concentration of one pure metal.

bismuth-cadmium, and arsenic-lead are alloy systems of this type. In Fig. 2.8b, the eutectic point is located at very low concentrations of one metal. This case is easily visualized as almost complete fore-

shortening of one side of the Fig. 2.6 diagram. Aluminum-beryllium, aluminum-tin, and bismuth-copper have diagrams of this type.

Monotectic Systems. This type of system contains the constant temperature (isothermal) reversible reaction $L_1 \rightleftarrows \alpha + L_2$. That is, one liquid phase L_1 transforms at constant temperature into a solid phase α and a second liquid phase L_2. Figure 2.9 illustrates a constitution diagram of this type. The monotectic point is point 2 on the diagram, and line 1–2–3 is the monotectic isothermal. An alloy of
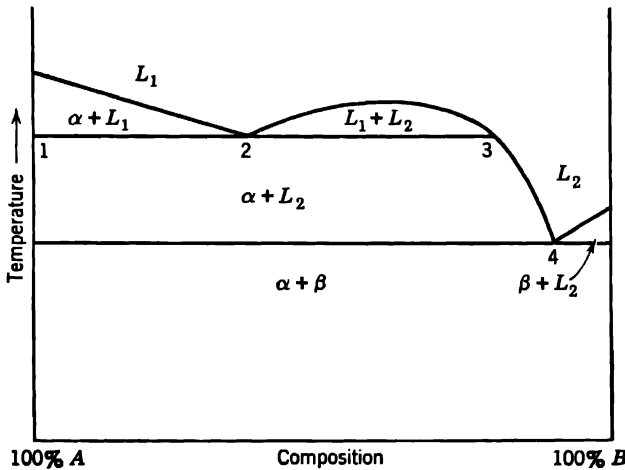
FIG. 2.9. Composition diagram illustrating monotectic reaction, point 2. Eutectic reaction also occurs at point 4.

this system having the monotectic composition, point 2, would, at constant temperatures, transform from liquid of monotectic composition into α grains and liquid L_2, which is less rich in metal A than L_1. Further cooling causes the eutectic transformation, point 4, and formation of α grains in a matrix of β. This type of system is rare, but examples are zinc-lead and copper-lead. The solubilities of the components of these two alloys are very small for each other, and for that reason they are often considered insoluble. Small additions of lead to copper appear as β globules in the copper, and promote machinability.

Peritectic Systems. The peritectic reaction may be designated as an isothermal reversible transformation of the type $\alpha + L \rightleftarrows \beta$. That is, a solid phase α and a liquid phase L transform at constant temperature to a second solid phase β. Alloy systems that possess a peritectic reaction are not altogether rare. High-zinc brasses are

perhaps the most common example, but the reaction also takes place at high temperatures in low-carbon steel and in tin-antimony, aluminum-iron, aluminum-nickel, copper-silicon, and copper-tin alloy systems, to name a few.

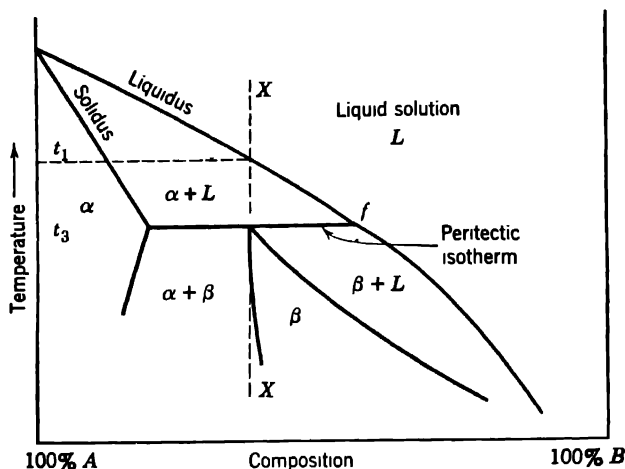The general form of a peritectic reaction on the constitution dia-

FIG. 2.10. Form of peritectic reaction on a constitution diagram.

gram is depicted on Fig. 2.10. Upon cooling of alloy $x-x$, the melt begins precipitating primary grains of α, as t_1 is reached. Further cooling results in more precipitation of primary α, moving composition of the remaining liquid toward f until t_3 is reached. At this temperature the remaining liquid will react with the previously formed α grains producing β grains having composition $x-x$. The reaction takes place around the primary α grains, hence the designation peritectic from the Greek *peri*, meaning "around." A wall of composition β is first formed, and this layer obstructs access of liquid to the α grains inside. The reaction then proceeds slowly by diffusion until all the solid has a uniform β composition. If the total original composition lies just to the left of composition $x-x$, there will be an excess of α grains remaining when the reaction is complete, and the excess pure grains of α will be surrounded by composition β. For compositions to the right of $x-x$, there will be an excess of liquid, and β grains in liquid L will remain when the reaction is complete.

The peritectic reaction involves transformation of a liquid phase and a solid phase into a uniform solid phase of different composition.

The original primary grains may be either a pure metal or a solid solution, and the resulting solid grains may be an intermediate phase or a solid solution in particular alloys.   Often, several peritectic re-
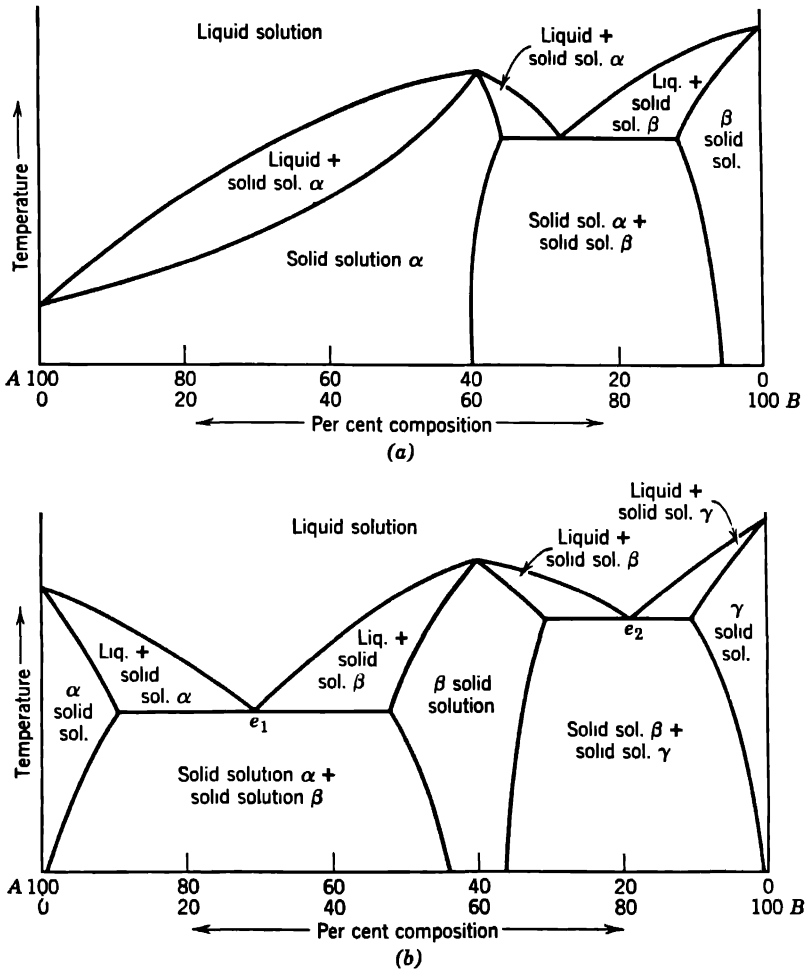

FIG. 2.11.   Constitution diagrams for two systems that form an intermediate phase.   (a) Soluble with metal A, partly soluble with metal B.   (b) Partly soluble with both metals A and B.

actions at successively lower temperatures will occur in a single binary system of this type.

Systems Containing Intermediate Phases.   Many binary alloy systems contain an intermediate phase that melts at constant tem-

perature, behaving in this respect like a pure metal. The constitution diagrams for alloys containing an intermediate phase are most easily understood by considering them as two separate diagrams, one of alloys between pure metal *A* and the intermediate phase, and the second as alloys of the intermediate phase and pure metal *B*. Each of these portions of the constitution diagram may be of one of the forms already discussed. In Fig. 2.11, two typical examples are illustrated. Sometimes there may be more than one intermediate phase in the
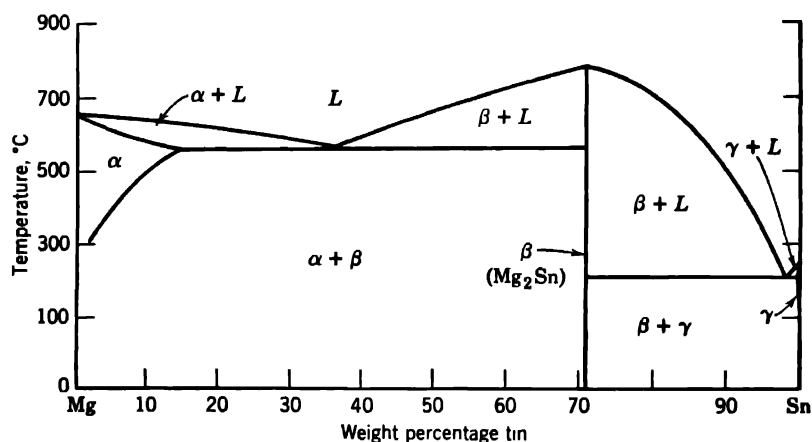
Fɪɢ. 2.12. Constitution diagram for magnesium-tin binary-alloy system. Note intermetallic compound, Mg_2Sn.

system, as for beryllium-nickel. In this case the diagram is considered as containing additional segments, as described for a single intermediate phase.

A special case is the formation of an intermetallic compound in the binary system. Magnesium is prolific in this respect, since it forms intermetallic compounds in the calcium, copper, tin, silicon, and lead systems. Fig. 2.12 illustrates the constitution diagram for magnesium-tin alloys. As with congruently melting intermediate phases, this diagram may be considered as an alloy of magnesium and the beta phase, Mg_2Sn, and an alloy of the beta phase, Mg_2Sn, and tin.

The above constitute the typical reactions which take place in solidification of binary alloys. Some of the alloys are purely of one of the types illustrated. Others are complicated with presence of one or more intermediate phases and possibly with one or more eutectic or peritectic reactions. The complexity of these more difficult types

can be reduced by dividing each portion of such diagrams into the fundamental types discussed.

2.11 NONEQUILIBRIUM SOLIDIFICATION

The solidification reactions just described presume that equilibrium is maintained during cooling. When the cooling rate exceeds that required for equilibrium, as often occurs industrially, the solidification will not obey the solidus of the constitution diagram. Instead,
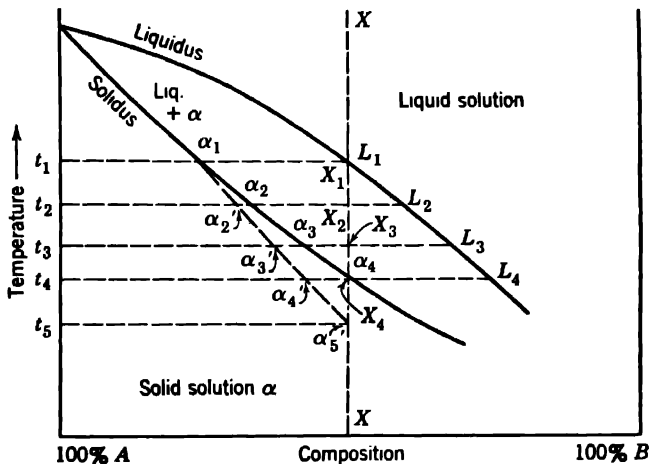

Fig. 2.13. Solidification of a completely soluble alloy at nonequilibrium cooling rate, producing coring.

the solidus will, in effect, be depressed to lower temperatures, and the alloy liquid is said to be *supercooled* before freezing is complete. Absence of alloying elements or impurities which promote nucleation increases the degree to which this will occur.

The effect of nonequilibrium cooling on alloys is to produce a smaller grain size and to lower the freezing temperatures. In addition, those alloy reactions that attain equilibrium through diffusion (differences in solubility, peritectic reactions, and eutectic reactions) will often be arrested before uniform chemical composition is attained. The composition of such grains will differ from the grain center outward, a characteristic known as *coring*. Additional phases may also be present if the depression of the solidus intersects new phase boundaries. Many alloys possess cored structure as cast from the melt.

The manner in which coring occurs in a completely soluble alloy is indicated in Fig. 2.13. With the normal rate of cooling accompanying freezing there is insufficient time for the diffusion process to maintain equilibrium between the liquid state and the solid state, and so the following departure occurs. When the alloy x–x cools to the liquidus at t_1, freezing begins by separation of crystals of α_1.
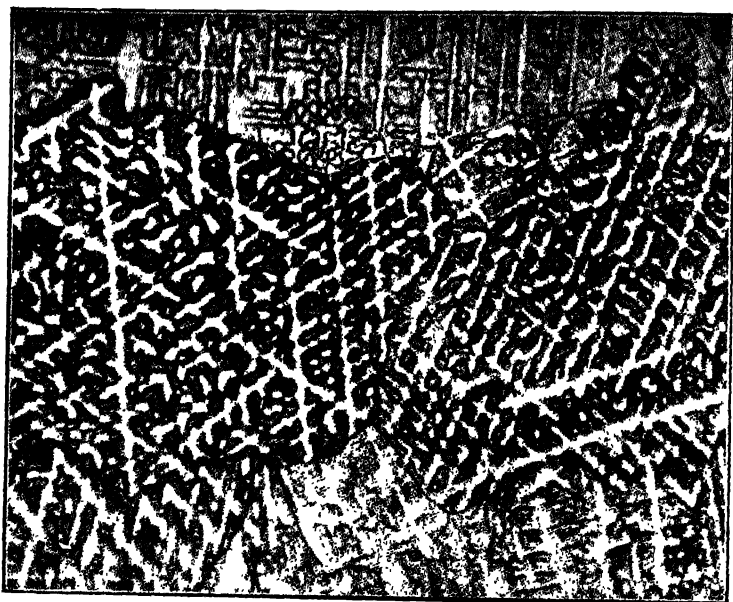

FIG. 2.14. Photomicrograph of a copper-nickel alloy (85 Cu. 15 Ni) showing cored dendritic structure. White areas are nickel-rich solid solution. Dark areas are copper-rich solid solution ($\times 100$).

When cooling reaches temperature t_2, crystals, of α_2 are freezing but the solid α_1 which froze at temperature t_1 has not yet increased in B content to α_2. The average composition of the α phase at t_2 is actually α_2' instead of α_2. The relative proportions of liquid and solid at t_2 are:

$$\% \, \alpha = \frac{X_2 L_2}{\alpha_2' L_2} \cdot 100 \qquad \% \, L = \frac{\alpha_2' X_2}{\alpha_2' L_2} \cdot 100$$

There is therefore more liquid and less solid present at t_2 than there would be under equilibrium conditions. When the cooling reaches temperature t_4, there is $(\alpha_4' X_4 / \alpha_4' L_4) \cdot 100 =$ per cent of liquid remaining. Under equilibrium conditions no liquid would remain at t

When equilibrium is not maintained, it is not until t_5 that the average composition of the α phase reaches that of the gross composition, and the freezing is complete. As a result of this manner of freezing, solid α is laid down in a continuous series of layers beginning with the highest melting α_1, richest in A component, at the inside, and ending with the lowest melting α_5, richest in B component, at the outside.

The photomicrograph, Fig. 2.14, of a copper-nickel alloy (85 Cu, 15 Ni) illustrates such a cored structure. It is a solid solution alloy consisting of a single phase. The white areas are nickel-rich solid solution grading to the dark areas which are copper-rich solid solution. The nickel-rich material solidified first, forming the skeleton of a dendrite, and the copper-rich material then solidified in the interstices of the nickel-rich core.

Coring could be avoided by freezing slowly from the melt, but large grains would result and a long time would be required for complete diffusion. The industrial practice is to chill cast alloys to fine grain size and then to equalize the coring through diffusion during hot working, or by annealing, often with intermediate cold working.

2.12   EQUILIBRIUM CHANGES IN THE SOLID STATE

The principles developed for liquid-solid transitions, paragraph 2.10, apply equally well for changes that may occur in particular alloys in the solid state. The most general type could possess a separate constitution diagram, having one of the forms previously discussed, below its diagram for solidification. The lower diagram would indicate changes that take place in the alloy in the solid state under equilibrium conditions. Such changes might result from decrease or increase in solubility, from allotropic transformations, and from formation of ordered lattices at temperatures well below solidification. The processes of nucleation and growth of new phases apply in the solid state as they do in solidification.

These characteristic changes may also occur at temperatures near solidification in such manner as to connect the phase fields with the liquid-solid transition. Two examples of this type will be described.

Change in Partial Solid Solubility.   This example is obtained in soluble-liquid, partly-soluble-solid alloys, Fig. 2.6, in which the phase fields for α and β decrease with reduction in temperature, Fig. 2.15. When solidification of alloy x–x is complete under equilibrium conditions, it will consist of one single phase which is composed of grains of α solid solution (B in A). Further reduction in temperature finds

no change in the structure until the temperature t_4 is reached. Composition $x-x$ intersects the decreasing solubility line $p-u$ at this temperature, and further reduction in temperature causes precipitation of β solid solution. The β precipitates at the grain boundaries and on the crystallographic planes of the α solid solution. For the alloy type shown, the precipitate of fine grains of β would be another solid solution, but in other alloys it may also be a nearly pure metal or an intermediate phase. Intermetallic compounds are especially impor-
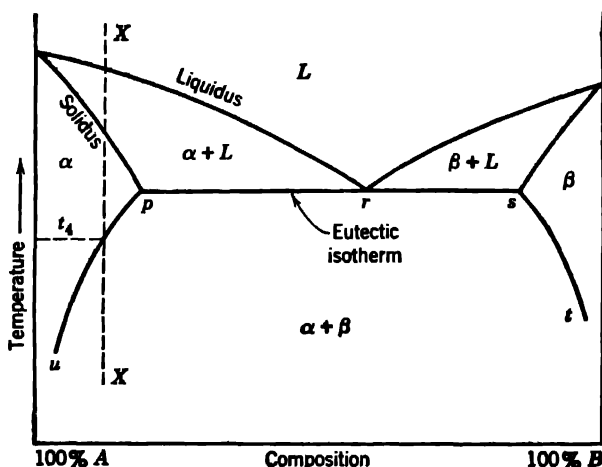
Fig. 2.15. Constitution diagram for partly soluble alloy system, with decreasing solubility in the solid state.

tant because they strengthen and harden the host phase. Aluminum-copper alloys which are hardenable by heat treatment are of this type.

Eutectoid Reaction. The eutectoid reaction occurs in only a few alloys but is of importance because it is a principal mechanism in the hardening of steel by heat treatment. In this reaction, one-phase solid metal decomposes into two solid phases, designated $\alpha \rightleftarrows \beta + \gamma$. This is analogous to the eutectic reaction in which a one-phase liquid solution transforms into two solid phases. The temperature at which the reaction takes place is known as the *eutectoid temperature.*

Eutectoid composition at 0.83 per cent C is shown in Fig. 2.16 as it occurs in steel. This alloy consists of the single phase, γ, at temperatures between 723 C and 1350 C. At 723 C the single-phase grains of γ transform under equilibrium cooling forming the solid phases α (practically pure iron solid solution which 0.08 per cent carbon) and Fe_3C (intermetallic compound, iron carbide) in an inti-

mate mixture of grains, which, in steel, are lamellar layers called *pearlite.*

A composition having less carbon than the eutectoid composition (0.83 per cent C) will precipitate over a range of temperature starting at the intersection with line *G–S*. Alpha solid solution precipitates
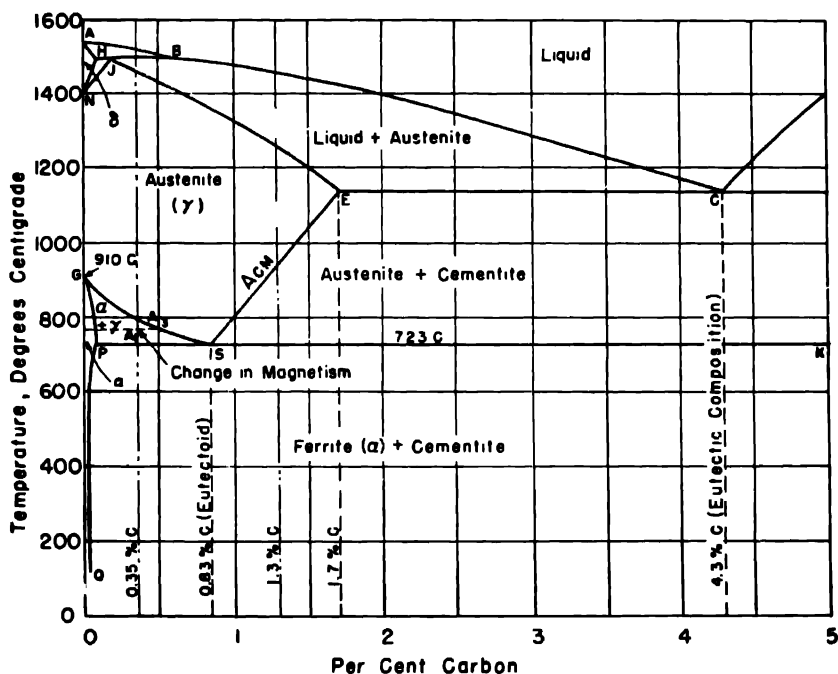

Fɪɢ. 2.16. Constitution diagram for iron-carbon alloys to 5 per cent carbon, showing eutectoid reaction in solid state. Note that eutectic and peritectic reactions are also present.

first in the grains and grain boundaries of γ, until at 723 C the remaining γ precipitates as lamellar layers of α and Fe₃C. Equilibrium structures of these alloys below the eutectoid thus consist of a network of primary o around the lamellar areas of α and Fe₃C.

The intermetallic compound precipitates first in hypereutectoid (higher than eutectoid) alloys upon intersection with line *S–E*, and again at 723 C the remaining γ precipitates as α and Fe₃C lamellas. Equilibrium structures of hypereutectoid alloys therefore consist of primary carbides in a network around the pearlitic areas.

Ordering Reactions. These reactions have not been important industrially because they have not occurred frequently in commercial

alloys at the processing and treatment temperatures normally used. Yet, ordering is a phenomenon that may become important with developments in low temperature treatment procedures, since it customarily involves a significant change in alloy properties as compared with the same composition with disordered atomic arrangement. Ordering occurs in nineteen known alloy systems at temperatures far below the liquid-solid transition. The reaction is merely shown by
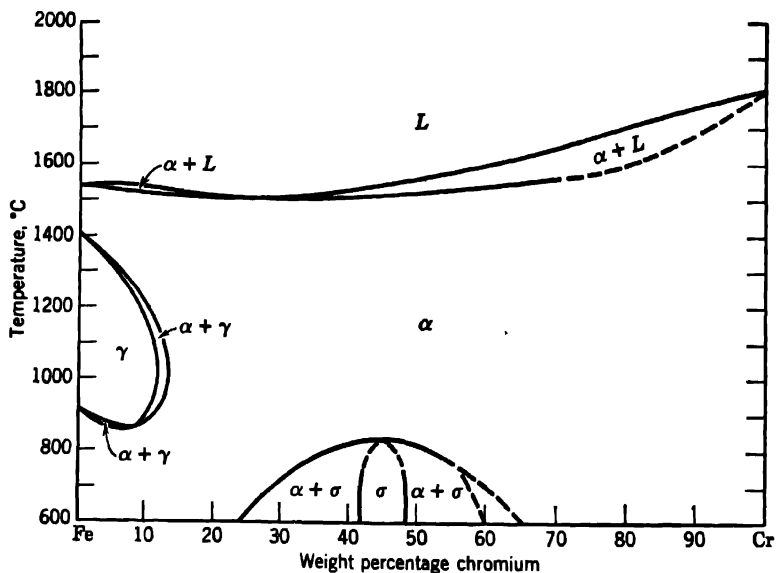

FIG. 2.17. Constitution diagram for the iron-chromium system, showing an ordering reaction. Note minimum liquidus.

the two-phase field, σ, indicated in Fig. 2.17, for the iron-chromium system. The ordered phase, as for intermetallic compounds, may also possess the ability to form solid solutions with excess percentages of either constituent and these, too, are indicated by the $\alpha + \sigma$ fields on the constitution diagram.

2.13 COMMERCIAL ALLOYS

Alloys used in commercial quantities usually fall into one of three types made up of the solidification and solid-state reactions already discussed. These three types are:

(a) Solid-solution alloys.

(b) Precipitation-hardening alloys.

(c) Iron-carbon alloys.

In (b) and (c), cooling rates that suppress equilibrium cause considerable change in the solid-state reactions just described. Such changes, together with the properties of these general alloy types, are briefly discussed in the following paragraphs.

2.14 SOLID-SOLUTION ALLOYS

Alloys of this type are formed by any of the compositions in the systems depicted in Figs. 2.4 and 2.5, or by the compositions within the partial-solubility ranges of systems like Fig. 2.15. Upon slow cooling from the melt they consist of a single solid-solution phase, either of substitutional or interstitial type. Some of them form ordered substitutional lattices at low temperatures. All have cored grains of a single phase if cooled from the melt at rates that do not permit equilibrium to be attained.

Effect of Concentration on Properties. Increasing proportions of the alloying element in binary solid solutions cause a change in the properties of the original base metal. Some properties obey the law of mixtures; others are more widely changed.

Those that follow the law of mixtures are the elastic tensile, compression, and shear moduli, the coefficient of thermal expansion, specific heat, density, and lattice parameter. That is, these properties of the alloy are in proportion to the properties and amounts of each component element present.

Properties that vary widely with alloying-element additions are mechanical resistance (formability, strength, and hardness), electrical resistance, and thermal resistance.

The hardness and mechanical strength of completely soluble alloys increase to a maximum at 50 atomic per cent of each element (see Fig. 2.18), and formability correspondingly decreases. This is a surprising characteristic and offers one method of strengthening certain pure metals at a sacrifice in their formability. The industrial brasses and bronzes, lead, and many aluminum alloys are of this type, wherein increased strength is obtained by additions of zinc, tin, etc., all elements of low strength in themselves (see Fig. 2.19).

Electrical and thermal conductivity in this type of alloy drop off rapidly with additions of either element to the other (see Fig. 2.18). Thus, solid-solution alloying is effective in increasing these resistances of a pure metal.

In alloys of limited solubility, the law of mixtures prevails for the resistance properties (strength, hardness, electrical, and thermal) in the region where the alloy consists of two phases. The properties

for an alloy of these compositions is in proportion to the properties and amounts of each of the two solid solutions present. The law of mixtures applies similarly for alloys in a two-phase field in which one is an intermetallic compound, or for relatively insoluble solid alloys. Ordering acts similarly to a separate pure-metal boundary of a continuous field by adding peak cusps to the electrical conductivity, thermal conductivity, and magnetic properties, and causing minima in mechanical strength at the ordered composition.
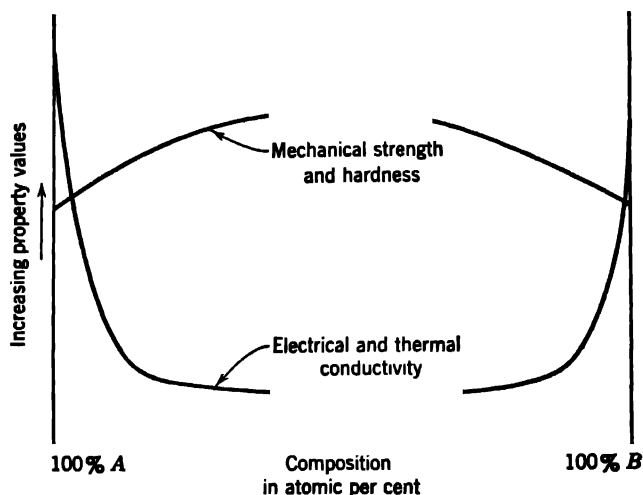
FIG. 2.18. General effect of composition on resistance properties of solid-solution alloys. (Electrical and thermal resistance are reciprocal of conductivity.)

Effect of Grain Size. Solid-solution alloys, in common with all types, possess improved mechanical properties at room temperature when of fine grain size. The finer grain size results in many interruptions in the slip planes and enhances the effect of those planes poorly oriented with the direction of loading. Consequently, the elastic resistance to deformation, the strength, especially to suddenly applied loads, and the hardness tend to be increased with a decrease in elongation. Large, coarse grains, especially in the as-cast condition, tend toward markedly low mechanical properties, actual brittleness, and low shock resistance. Coring also tends to increase brittleness of cast structures.

Effect of Cold Work. The effect of cold work on these alloys is illustrated in Fig. 2.20 for red brass (85 Cu, 15 Zn). The tensile strength, hardness, proportional limit, and elastic limit increase

rapidly and in near proportion to the degree of cold work, although for most alloys the elastic properties increase more rapidly. Elongation, by contrast, rapidly decreases. The effect on electrical conductivity
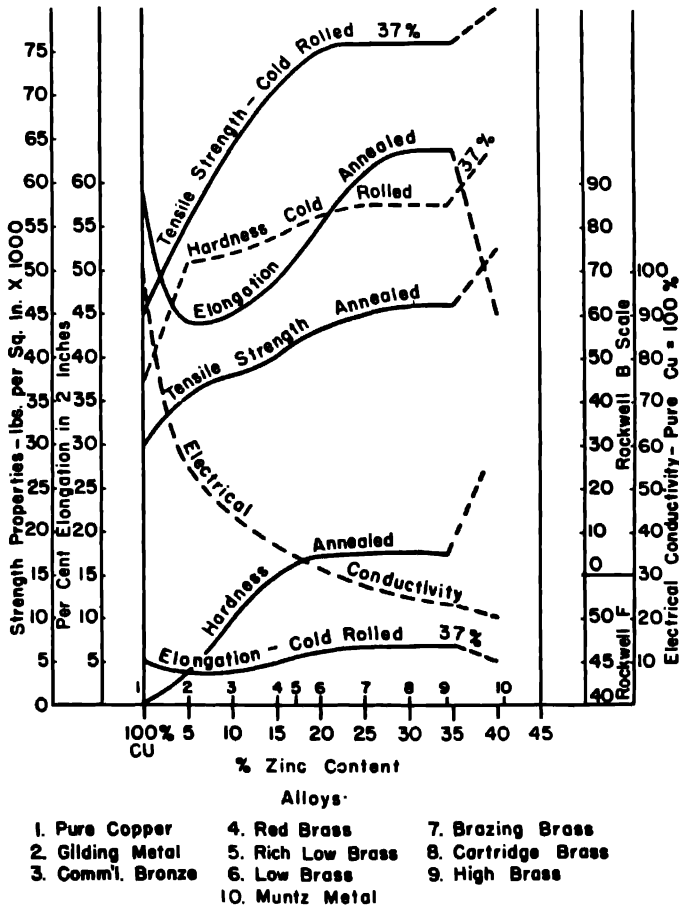

FIG. 2.19. Mechanical properties of copper-zinc alloys (brasses) annealed and cold worked to 37 per cent reduction in section.

is small, amounting to decreases of approximately 2 per cent for 37 per cent reduction in thickness and 2½ per cent for 60 per cent thickness reduction.

Elongated or strained grains retained from cold working lead to variations of properties between with-rolling and trans-rolling directions. This variation is minor and is often disregarded for cubic lattices, such as for copper and aluminum alloys, but may be as

much as 30 per cent difference for hexagonal lattices as for zinc and its alloys. Large amounts of cold working in a preferred direction increase the degree of this variation as in pure metals.
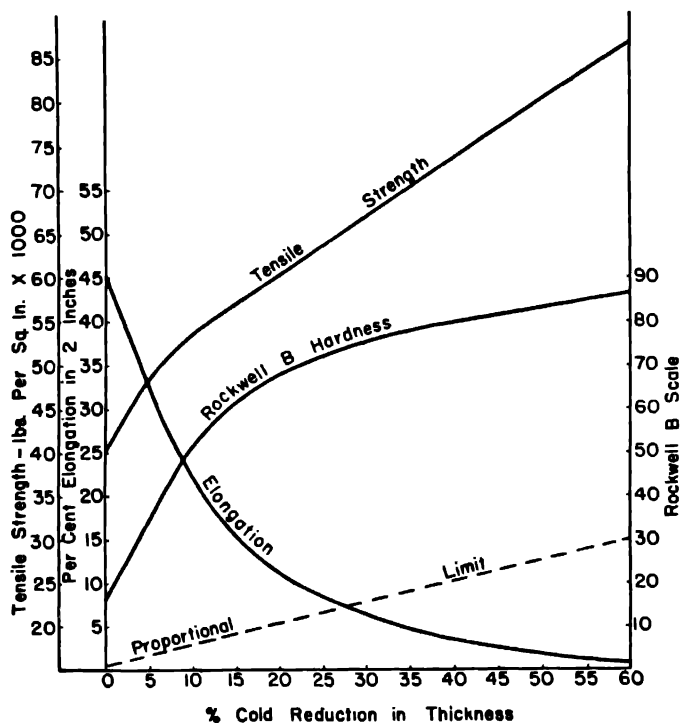
Fig. 2.20. Effect of cold work on mechanical properties of 85 Cu–15 Zn red brass.

Effect of Heat Treatments. Solid solutions behave much like a pure metal under heat treatment. The processes of recovery (strain relief), recrystallization, and grain growth occur successively in cold-worked alloys with increased temperature. The temperature for these processes is reduced by longer time at temperature and by increased degree of cold work before heating. The effect of cold work on these processes is reduced by larger grain sizes before working.

The final grain size after recrystallization is dependent mainly on the degree of cold work and to a lesser extent on the temperatures used. The processes and properties are illustrated in Fig. 2.21, which is similar to Fig. 1.11.
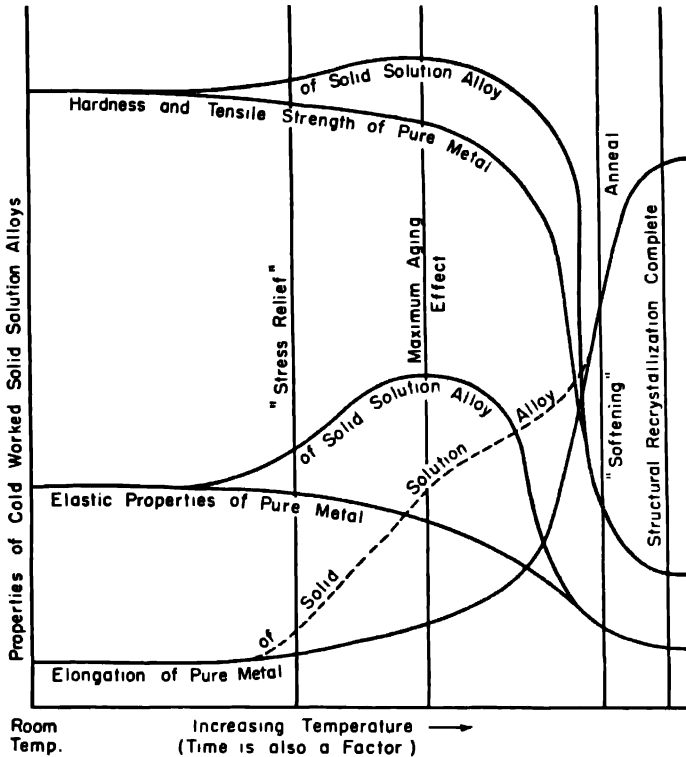

FIG. 2.21. Recovery and recrystallization in cold-worked solid-solution alloy. Dotted lines show properties obtained by long-time aging treatments.

Heat treatments are also given to the as-cast alloy, without cold working, to homogenize the cast structure. Temperatures involved are about the customary recrystallization temperatures to provide the atoms with enough mobility to eliminate dendritic segregation and coring through diffusion. The temperature is held long enough for these changes to occur, and is followed by slow cooling to avoid thermal strain.

Recent research indicates heat treatment of cold-worked solid-solution alloys can result in coincident increases of elastic properties, hardness, elongation, endurance limit, and electrical conductivity

(see Fig. 2.21). The strained material is heated for relatively long periods of time at temperatures below the recrystallization range. Although research results are not yet conclusive, it seems probable that either precipitation or formation of an ordered lattice is induced. Such heat treatment is already being applied in industry, one such example being steel shells.

2.15 PRECIPITATION-HARDENING ALLOYS

Alloys of this type possess one, or more, precipitation reactions within a solid-solution lattice, similar to that described in Fig. 2.15. The precipitating phase may be an essentially pure metal, another
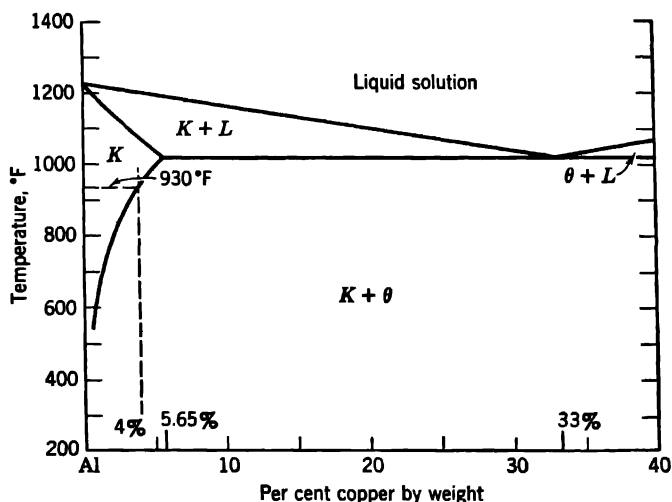

Fig. 2.22. Constitution diagram for the aluminum-copper alloy system to 40 per cent copper by weight.

solid solution, or an intermetallic compound. There are approximately two hundred precipitation-hardening alloys in industry today. In the majority of these alloys, the precipitating phase is an intermetallic compound.

An aluminum-copper alloy having approximately 4 per cent copper, known commercially as Duralumin, will be used for illustration. The portion of the Al-Cu constitution diagram which shows decreasing partial solid solubility of Al for Cu is given in Fig. 2.22. The liquidus starts at 1220 F, the melting point of pure aluminum, and drops to the eutectic temperature, 1018 F, at 33 per cent copper. The K phase field has a face-centered cubic lattice and is a substitutional solid

solution of copper in aluminum. The maximum solubility of copper is 5.65 per cent at the eutectic temperature, decreasing to 0.25 per cent at room temperature. The 4 per cent composition line crosses the decreasing solid solubility line at 930 F.

At temperatures above 930 F and below the solidus line the alloy consists wholly of K solid solution. If coring has been eliminated by slow cooling from the melt, or by working and annealing, or by homogenization treatment, the grains of K will be uniform, with copper atoms substituted at random in the face-centered cubic lattice.

Cooling of the alloy at a slow near-equilibrium rate produces no change until 930 F is reached. At this temperature the θ phase begins to precipitate at the grain boundaries and on the slip planes within the K grains. This second phase is an intermetallic compound of Al_2Cu and has a tetragonal lattice structure. Further cooling at the slow rate causes further precipitation until at room temperature the alloy will consist of 0.25 per cent copper in solid solution as small grains of K, which form a network around larger grains of θ containing the remaining 3.75 per cent copper. In this condition the alloy is said to be annealed. Its mechanical strength and hardness are at low values, whereas ductility and electrical conductivity are moderately high.

Nonequilibrium cooling of the 4 per cent copper alloy from above 930 F does not permit completion of the precipitation reaction. In fact, with sufficiently rapid cooling, as by quenching from above 930 F in water, it is possible to retain all the copper in the K-phase solid solution at room temperature. Such a solid solution is said to be *supersaturated*, since more copper is in solution in aluminum than occurs under equilibrium conditions. The solution-quenched alloy is in its softest condition; its tensile strength, hardness, and electrical conductivity are at their minimum values while ductility is at its maximum.

All alloys of this type tend to precipitate from the supersaturated solution even at room temperature. The rates of diffusion determine whether precipitation will actually take place in a practical period of time. If precipitation does occur at room temperature, as it does for the 4 per cent copper aluminum alloy, the alloy is said to *age naturally*. Reheating to moderate temperatures is required for most alloys of this type to increase the diffusion rates and cause precipitation, a process termed *artificial aging*. The melting point of the host metal is a rough indication as to whether precipitation will follow at room temperature or at elevated temperatures. For example,

(*a*) most lead-base alloys will age at room temperatures or at even lower temperatures, (*b*) zinc-base alloys will age from room temperature up to about 200 C, (*c*) some aluminum-base alloys age naturally at room temperature over a period of weeks and months and even years, whereas a few require artificial aging at temperatures up to 200 C, (*d*) many copper-base alloys require aging in the range of 200 to 600 C to effect precipitation, and (*e*) most iron-base alloys must be aged in the range of 400 to 900 C.

The first effect of reheating for precipitation is to relieve the strains of quenching. Then, with longer time or higher temperature, as precipitation starts, tensile strength, hardness, and electrical conductivity begin to increase while ductility drops off. As the reaction progresses a critical size and dispersion is reached at which hardness, tensile strength, and electrical conductivity increase to a "maximum combination" of properties, with ductility at a minimum. Further increase in aging temperature or time at temperature results in *over aging*. The precipitated phase coalesces and grows large grains; tensile strength and hardness decrease rather abruptly, whereas electrical conductivity and ductility tend to increase somewhat with the grain growth.

These variations in properties are diagramed in Fig. 2.23. Even those alloys, e.g., Duralumin, that age naturally over a period of weeks to practically full strength must nevertheless be artificially aged to insure consistent results, to relieve the quenching strains, to prevent shipments of articles incompletely aged, and to eliminate the cost of storage while aging naturally.

Thus, the precipitation-hardening reaction in most of these alloys can be controlled to effect, in each case, the most useful strength properties. The alloy is (1) given a *solution heat treatment* by heating and holding at temperature until all the alloying element is in solid solution. It is then (2) *quenched* to suppress the normal phase change and to form a supersaturated solid solution. An *aging treatment* (3) follows, to control the degree of the phase precipitation and to obtain the desired properties.

Effect of Cold Work Intermediate to Quenching and Aging. The only difference between precipitation hardening of cast alloy and a hot- or cold-worked alloy is that the previously worked alloy is more dense than the same material cast. The difference in properties is slight, except for ductility, which is usually markedly improved by the previous working.

The effect of cold working after the solution quench and previous to reheating for precipitation is twofold: maximum precipitation-hardening properties are increased, and the temperature and time for precipitation are decreased somewhat. These effects, of course, de-
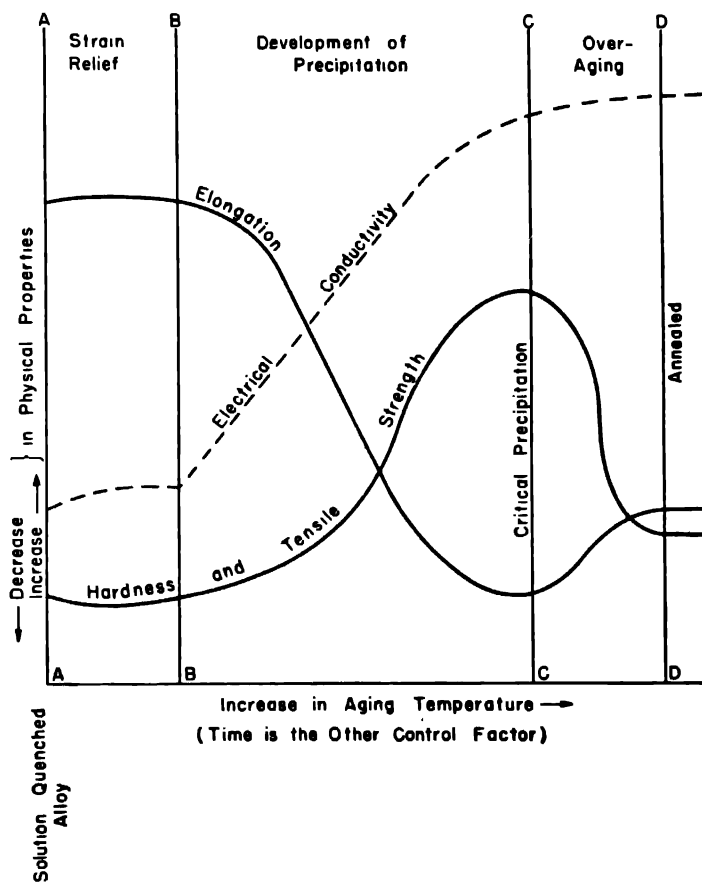

FIG. 2.23. General effect of precipitation on properties of precipitation-hardening alloys.

pend upon the amount of strain from cold work, and this, in turn, varies with alloy composition. Too much cold work will result in internal ruptures and checks, with resultant lowering of elastic properties, elongation, shock resistance, etc., even though the tensile strength and hardness may be increased. In general, copper-base alloys of this type should not be cold reduced more than 50 per cent

without intermediate solution treatments. Aluminum-base alloys may be cold reduced more than 50 per cent, but many aluminum alloys thus treated tend to concentrate precipitation in grain boundaries and along distorted slip planes, which results in marked embrittlement and lowered corrosion resistance. Chiefly for these rea-
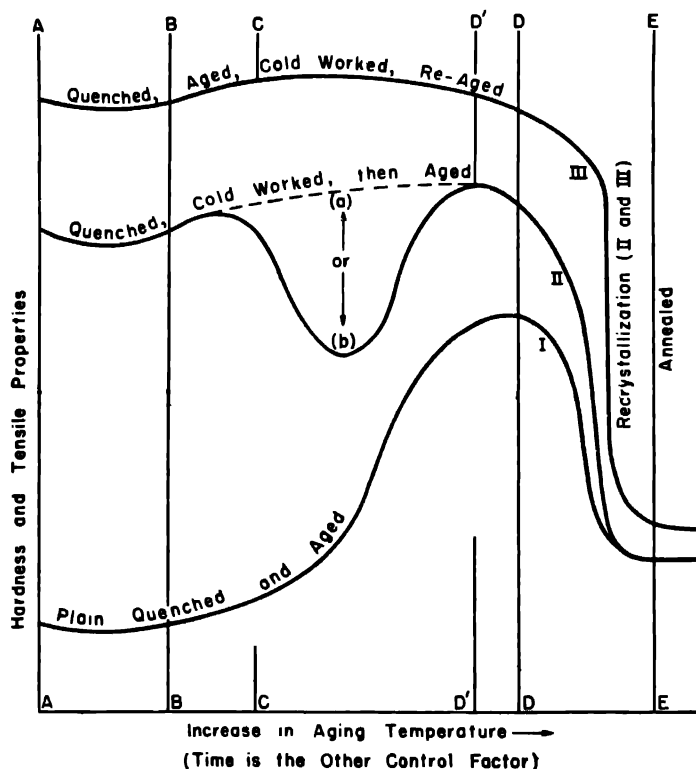

FIG. 2.24. Effect of cold work combined with precipitation in precipitation-hardening alloys.

sons, copper-base alloys of this class, which have sufficient elongation as solution quenched, are cold rolled to shape then aged to obtain the final tensile properties. The aluminum-base alloys that are structurally sensitive to embrittlement are solution quenched and aged *after* cold forging or shaping.

Curve II of Fig. 2.24 shows the characteristic effect of precipitation hardening of a cold-worked supersaturated solid solution on hardness and tensile properties. The first effect is strain relief from *A* to *B*. From *B* to *D'*, the cold-worked supersaturated solution takes one of

two paths. Either some effective precipitation occurs before any recrystallization, as in curve *a*, thus maintaining and perhaps increasing the cold-worked solution properties; or some recrystallization effect takes place, as in curve *b*, before precipitation becomes effective to stabilize the remaining cold-work properties and even to cause a further increase to maximum properties at *D'*. The effect of intermediate cold work is to increase maximum hardness and strength and to decrease the maximum age-hardening temperature (or time) from *D* to *D'*.

Effect of Cold Work after Complete Precipitation Hardening. A few alloys still retain enough ductility for subsequent cold working after precipitation hardening. Maximum combination properties are achieved in such alloys by cold working after complete precipitation hardening.

The effect of re-aging (*double aging*) alloy material that has been previously precipitation hardened and then cold worked is shown by Curve III in Fig. 2.24. The first effect is that of strain relief. The next effect is to cause some further precipitation (at *C*), induced by cold working the solid solution matrix of the previously precipitation-aged material. From *C* to *D'* the properties remain relatively unaffected. Actual structural recrystallization, coincident with over aging, takes place between *D* and *E*. By this third treatment, the cold-worked effect and properties are maintained (stabilized) until the service temperature actually exceeds that for maximum age hardening (at *D*). This treatment is a relatively new development and is finding its way into industry today for several special alloys, one of which is Cu, 0.4 Cr, 0.1 Be.

Effect of Concentration on Properties. The effect of increasing proportions of the alloying element in these alloys in the annealed condition follows the principles discussed in the previous paragraph for solid-solution alloys. Compositions below the solid solubility limit have elastic moduli, coefficient of thermal expansion, density, and specific heat in proportion to the amounts and properties of the components. The resistance properties, mechanical, electrical, and thermal, are increased by the alloying addition in greater proportion than the law of mixtures would indicate. Annealed alloys with precipitated phases present possess all properties in proportion to the amounts and properties of the two phases present and their distribution.

Increasing percentages of the alloying element (beyond the amount soluble at room temperature) increase the degrees of hardening pos-

sible by precipitation. The increase in potential strength and hardness is nearly linear, and is accompanied by a near-linear decrease in ductility. Compositions having the alloying element present in percentages beyond the eutectic temperature solubility become very hard and brittle on hardening if the precipitating phase is an intermetallic compound. In this condition they are difficult to form and consequently are little used.

Grain size has the same effect as for solid-solution alloys, as discussed in the last paragraph. The smaller the grains, the better the mechanical properties at room temperatures.

A few typical precipitation-hardening alloys are the beryllium coppers (2 Be, balance Cu; 0.4 Be, 2.6 Co, 97 Cu; and 0.1 Be, 0.4 Cr, 99.5 Cu), wrought-aluminum alloys (4 Cu, 0.5 Mn, 0.5 Mg, balance Al; and 4.5 Cu, 0.8 Si, 0.8 Mn, balance Al), cast-aluminum alloys (7 Si, 0.3 Mg, balance Al; 4 Cu, 96 Al), and cast-magnesium alloy (9 Al, 2 Zn, 0.2 Mn, balance Mg).

2.16 IRON-CARBON ALLOYS

These alloys depend on a phase transformation in the solid state that permits controlled precipitation of a new phase to cause hardening. The same general characteristics could be obtained with alloys that possess such solid-state reactions as the eutectoid and peritectic reactions, and the precipitated phase could be a pure metal, a solid solution, or an intermetallic compound. The most important of these, however, is the eutectoid type with precipitation of an intermetallic compound, since this is the reaction which occurs in steel. Discussion will be limited to this type and will be briefly illustrated with steel alloys.

Equilibrium cooling of an eutectoid alloy has been discussed in paragraph 2.12, with reference to Fig. 2.16. In steel, the hypoeutectoid (less than eutectoid, 0.83 per cent C) compositions attain a structure having a network of almost pure iron grains (α) surrounding areas made up of lamellar layers of the almost pure-iron (α) and the intermetallic compound, Fe_3C. Hypereutectoid compositions (more than eutectoid) similarly have a network of intermetallic compound grains surrounding the lamellar areas. The hypoeutectoid steels will be relatively soft and ductile below 0.5 per cent carbon. Higher carbon contents, including the hypereutectoid compositions, have increased strength and decreased ductility. The lamellar areas in both will be coarse because of the slow furnace cooling necessary to maintain near equilibrium.

Air cooling exceeds the near-equilibrium rates obtained by slow furnace cooling. The effect of increasing the cooling rate by this amount is to cause finer grain size by limiting the time available for grain growth during the eutectoid transformation. In this condition the lamellar layers are much finer and may measure as little as 0.5×10^{-6} in. thick. The hardness and strength are improved over the furnace-cooled alloy, and the ductility is slightly lowered.

Water quenching (very fast cooling) a plain carbon steel from the γ phase (austenitic) condition tends to retain all carbon in supersaturated solution in the α iron. The excess carbon atoms (over 0.08 per cent) strain the atomic arrangement to such an extent that a tetragonal lattice forms, intermediate to the γ and α cubic types. The resulting structure, which is known as *martensite*, appears acicular, or needlelike, when viewed under the microscope. Martensite is very hard, strong, and brittle.

Reheating of the hardened steel is commonly called *drawing, tempering,* or *drawing back*. This operation softens the martensite by first causing actual formation of the carbide (Fe_3C) particles from carbon held in supersaturated solid solution, and then by causing growth of these carbide particles and of α-iron grains (ferrite) having a normal α lattice. As the tempering temperature is raised, the degree of grain growth of these phases increases continuously, resulting in structures having less hardness but more ductility than the martensite. Over a range of temperature from 200 C to about 500 C, the structure formed consists of submicroscopic particles of carbide in α-iron. At higher tempering temperatures, this changes by indistinguishable degrees to a structure in which the carbides have grown sufficiently to cause a distinctly granular appearance. The spheroidized structure is the final stage of agglomeration, where the carbide particles have grown to such an extent as to be actually visible under the microscope as spheroids of carbide in a matrix of ferrite. The hardness and strength of these temper products of martensite decrease with continued agglomeration of the carbide particles until this spheroidized structure is obtained. At that point, the steel is relatively soft and ductile.

Thus the eutectoid decomposition of γ phase iron into α iron and carbide Fe_3C can be controlled to effect any of a range of strength properties. The alloy is (1) given a *solution heat treatment* by heating and holding at temperature until the alloying element is in solid solution. (2) The alloy is then *quenched* to suppress the normal reaction and to form a supersaturated solid solution which leaves the

alloy hard and brittle. (3) A *tempering* or *drawing* treatment follows, to control the degree of precipitation and growth of the two new phases and to obtain the desired properties. The steps taken in hardening of steel are similar to those taken for hardening precipitation-hardening alloys, as discussed in the previous paragraph. The reactions that take place, the temperatures, and the rate of heating or cooling, are, of course, quite different. Of special note is that the eutectoid alloy steel hardens in quenching, and its hardness is reduced by controlled reheating operations. The precipitation-hardening alloy is still soft and ductile after quenching and hardens during reheating.

In modern commercial practice, structures similar to those described are often obtained in steel by quenching to controlled temperatures for a period of time before cooling to room temperature. This method, in effect, controls precipitation and grain growth of the intermetallic compound upon cooling and avoids the reheating operation. Additional alloying elements affect, sometimes appreciably, the cooling rates necessary for controlling precipitation. Since these characteristics are of considerable importance, they will be further discussed in Chapter 7, together with the effects of alloying-element composition on properties.

Fine grain size effects an improvement in mechanical properties of these alloys just as described for solid-solution alloys. Cold-work effects on the annealed alloy are also the same as for solid-solution alloys, although the work that may be performed until cracking ensues is reduced with increased alloying element concentration. The hardened alloys have greatly reduced ductility and may be given only a small amount of cold work. Enough ductility remains, however, for such operations as spring forming and bar straightening.

2.17 OTHER PURPOSES OF HEATING ALLOYS

The hardening operations described for precipitation-hardening alloys and for iron-carbon alloys involve heat treatments. This has often led to the assumption that heat treatment is synonymous with hardening, but this is not true. The hardening heat treatments should be considered simply as types of treatment applicable to the types of alloys described. Hardening of a particular metal or alloy can also be produced without heat treatment, by forming solid solutions and by cold working.

Other typical purposes of the heat treatments used in industry are:

(1) Strain relief of metals having cold work or thermal strain, as in recovery treatments of all types of alloys and pure metals.

(2) Recrystallization and grain refinement of cold-worked metals, either solid-solution alloys or pure metals.

(3) Softening of cold-worked alloys or pure metals for further working, as in annealing (recrystallization).

(4) Homogenizing of cored cast structures by hot working, by cold working and recrystallization treatment, or by solution treating of phase-transformation alloys and furnace cooling.

(5) Removal of gases introduced in pickling or plating by heating at a moderate temperature for a period of time.

(6) Stabilizing the structure against dimensional changes under moderate temperatures by successive heating cycles to a temperature just above the ambient to be encountered.

2.18 CONCLUSION

The discussion in this chapter has covered the atomic arrangements and structures characteristic of binary alloys. Particular emphasis has been given to the effects of structure on the properties of the three typical classes of alloys.

Additional alloying elements will join together with these binary systems, forming additional grain mixtures, solid solutions, or intermediate phases. Some of these additional elements are added to alloys to absorb impurities which cannot be removed, or to mitigate the effects of such impurities. Others are added to serve as catalysts, or to participate in solidification or solid-state reactions of the types described. The effect produced in each case depends upon the manner in which the new elements alloy themselves with those already present. Properties of the more important engineering alloys, which are usually composed of several elements, will be discussed in Chapters 7 and 8.

Review Questions

1. Define the following terms: Alloy, alloying element, impurity, porosity, inclusion.

2. How may an alloying element arrange itself with a base metal in an alloy?

3. Define a phase and give examples. What is the phase rule and what information does it provide?

4. How may information for constitution diagrams be obtained?

5. What are the reactions for the following: congruently melting system, an eutectic, a monotectic, a peritectic, and an eutectoid?

6. Why is it desirable to avoid an eutectic composition when choosing a solder for "wiping" a joint?

7. Describe the phases and reactions that occur on the constitution diagram for one of the following: silver-cadmium, beryllium-nickel, bismuth-lead, or copper-zinc. (Reference, *Metals Handbook*, 1948 edition.)

8. What is coring? Why is it considered objectionable? How may it be eliminated?

9. What characteristic constitution diagram is required for precipitation hardening in a binary alloy? Describe the process and the structural changes that occur at each step.

10. What reaction occurs in the hardening of steel by heat treatment? Describe the process and the structural changes that occur at each step for a 0.50 per cent carbon steel.

11. In a solid-solution alloy, what effect does increase of alloying element concentration have on modulus of elasticity, specific heat, density, coefficient of thermal expansion, and mechanical, electrical, and thermal resistance?

12. How are properties of a solid-solution alloy affected by grain size, by cold work, and by heat treatment?

13. A box of Duralumin rivets was found stored in the stock room. The Production Department advises that they need them for production. Should they be passed into the factory or should they be given some treatment first?

14. What purposes other than hardening may be served by heat treatments?

3 METALLOGRAPHIC EXAMINATION

by MISS M. L. PARKER and D. W. LYNCH *

3.1 INTRODUCTION

An indispensable division of physical metallurgy is the science of metallography. *Metallography* is the study of the constitution and structure of metals and their alloys through the use of optical microscopes and, in specific cases, electron microscopes.

The mechanical and physical properties of a metal or alloy are to a great degree influenced by the internal arrangement and state of the grains of which it is composed, as described in Chapters 1 and 2. These grains vary in size from submicroscopic particles less than one-millionth of an in. in diam to large grains visible to the naked eye and more than an in. in diam. Small grains occur in precipitation-hardened alloys, whereas large grains occur in certain silicon steels for magnetic applications.

Much can be learned about the physical condition of a metal through metallographic examination. Internal stresses within metal can be detected by microscopic examination of the grain structure in which the stresses are indicated by the strained, or "cold-worked," condition of the individual grains. Annealed or unstrained grains show the absence of internal stress in a metal. Cast materials are easily distinguished from wrought materials. Chemical composition of a known alloy type is indicated by the percentage of the various phases observed in its microstructure. In like manner, nonmetallic impurities, secondary phases, cracks, seams, laps, grain boundaries, dendrites, slip bands, to mention a few, are detected by examination of the internal structure under the microscope.
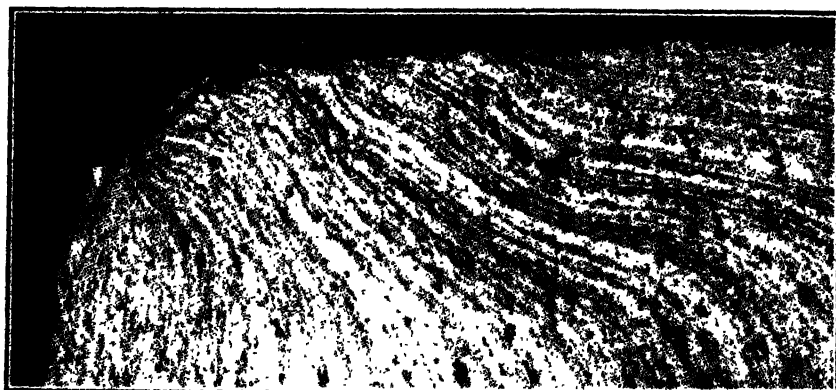
3.2 MACROGRAPHIC EXAMINATION

When the size of the structure or condition to be studied is large enough, the specimen may be observed with the naked eye or at very
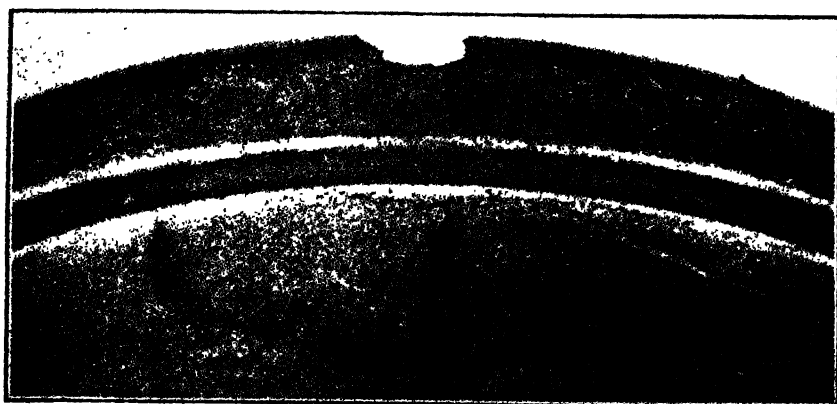
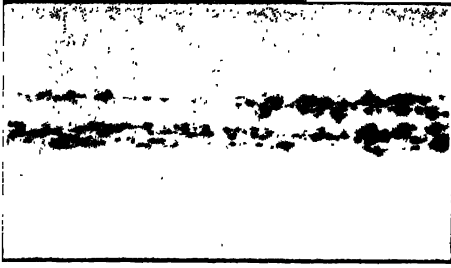* Works Laboratory, General Electric Co., Bridgeport, Connecticut.
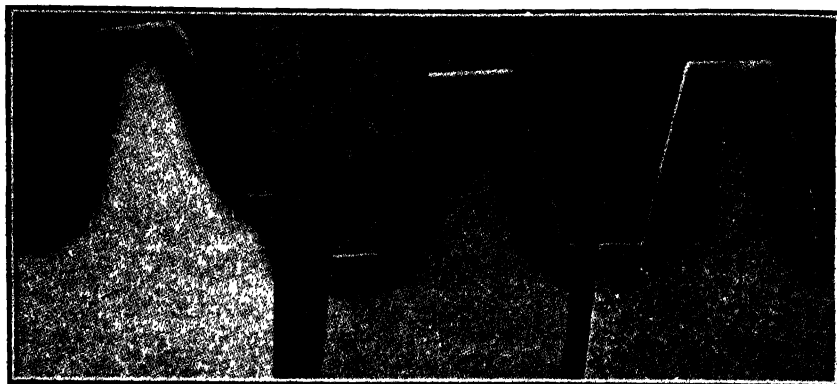
(a)

(b)

(c)

(d)
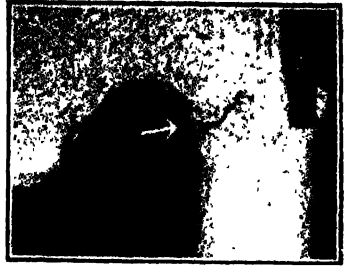
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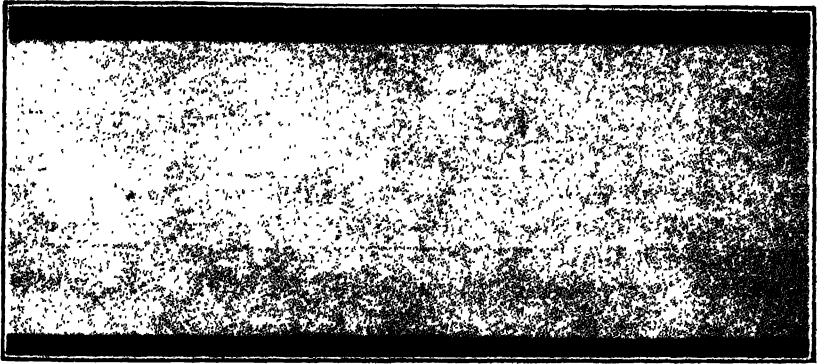
(f)
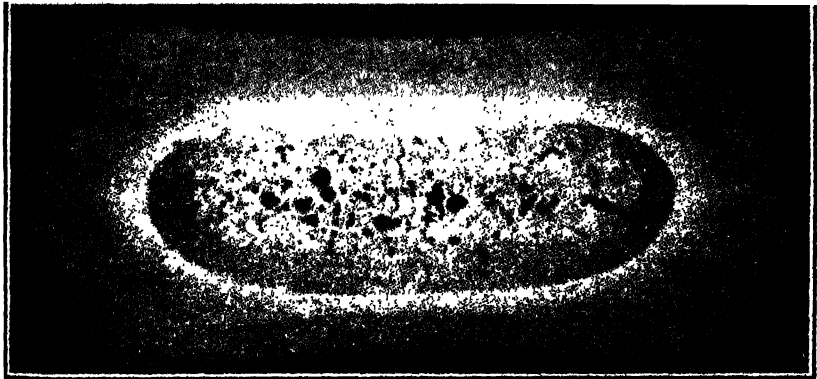
(g)

Fig. 3.1. Group of macrographs showing typical conditions analyzed at low magnifications. (a) Carburized (case-hardened) gear tooth (0.024 in.–0.032 in. depth of case). (b) Flow lines in aluminum at a punched edge ($\times$100—by metallograph). (c) Crack in a sintered iron bushing ($\times$5). (d) Pipe in low-carbon (or mild) steel ($\times$15). (e) Brass contact showing fracture crack ($\times$10). (f) Cracks in tungsten rod ($\times$6). (g) Porosity and cracks in aluminum spot weld ($\times$10).

low magnifications. Such observations made at a magnification of ×10 or less are called *macroscopic examinations.*

Extremely large grains are observed in this manner, as are case depths, weld structures, cracks, seams, fissures, porosity, fatigue patterns, and the like (see Fig. 3.1). Study of these structures at a higher magnification may not only be needless but, in many cases, misleading. In general, metallographic study is made at the lowest magnification that will resolve the particular structure under study;

3.3 MICROSCOPIC EXAMINATION

Structures whose components are too small to be studied by macroscopic methods are observed with the optical microscope at higher magnifications. Depending on the particular structure in question, magnifications up to ×1000 are commonly used, whereas magnifications from ×1000 to ×2000 are used less frequently. Higher magnifications are occasionally obtained with the optical microscope, but this higher magnification is the exception, not the rule, and is accomplished with difficulty.

The need for high magnifications with the optical microscope is well illustrated in the study of pearlite, a constituent common to normalized or annealed steels and gray cast iron. It may appear merely as a pearly, lustered area at lower magnifications, but at higher magnifications the alternate lamellas, or plates, of ferrite and carbide comprising the pearlite aggregate are easily distinguished. Very coarse pearlite, made up of thick plates, may be resolved at ×100, whereas finer pearlite still may not be resolved at ×1000 (see Fig. 3.2).

Where very high magnifications are necessary in order to give resolution of structure, an electron microscope may be used. Magnifications as high as ×50,000 are possible with it. Lamellar structures similar to pearlite, which may be too fine to resolve with the optical microscope, are studied in this manner.

3.4 PHOTOMICROGRAPHS

A photograph of the microscope image of a structure magnified more than 10 times is known as a *photomicrograph.* It provides a permanent record of the structure and facilitates study. It may be taken with a camera attachment to the microscope or with a metallograph. The metallograph consists of a inverted microscope, a perpendicular illuminator, using either a carbon arc, a tungsten arc, or

(a)

(b)

FIG. 3.2. Pearlite at different magnifications. (a) Gray cast iron at ×100. Pearlite not easily recognized. (b) Gray cast iron at ×500. Lamellas of pearlite easily resolved. Also note resolution of (1) "steadite" (phosphide-carbide eutectic) at center as pepperlike area, (2) graphite flakes (black), (3) manganese sulfide (gray inclusions), and (4) ferrite.

an incandescent light source, with an attached camera and bellows for taking photomicrographs.

Sample Preparation

3.5 SELECTION OF SAMPLE

The selection of the area to be studied and its preparation for microscopic examination play an important part in aiding the examiner to interpret his findings correctly. The structures of metallic materials cannot be studied microscopically unless the surface of the selected area is flat and scratch-free. This type of surface is obtained only after taking the material through a series of grinding and polishing steps. The final scratch-free, mirrorlike surface is etched to bring out internal structures for microscopic study.

In examining materials with directional properties, such as wrought metals, both transverse and longitudinal sections are studied. If the outside edge of the material is in question, samples from that edge plus one from the center are generally taken for comparison purposes. Where fractures or similar defects are concerned, the area immediately surrounding the fracture may be compared to an area away from it.

The size of the sample taken is dependent in part upon the area to be studied and upon the size of the mold available, if it is to be mounted prior to polishing for microscopic examination. Where a section to be studied is large, it may be prepared for study unmolded. Wire, thin sheets, edge sections, and other small pieces are generally molded in mounting mediums such as plastic resins. Sections up to 1 in. in diameter and ½ in. in height can usually be mounted conveniently in molds. The mounting of several small pieces at one time is often especially helpful for comparison purposes.

3.6 SECTIONING OF SAMPLES

Hack saws or cut-off wheels are generally used for sectioning materials. If a cut-off wheel is used, a coolant is desirable while cutting, to avoid overheating the material and possibly altering its structure. Some materials are brittle enough so that sections can be easily broken from them. With all materials, the utmost care must be taken in obtaining the sample for study.

3.7 SAMPLE MOUNTING

Several mounting mediums are available, but Lucite (thermoplastic) and Bakelite (thermosetting) mediums are most commonly used. Wood's Metal, Litharge (mixed with glycerine), or Selectron (a room-temperature setting, catalyzed resin) are used for mounting samples that cannot withstand the heat (250–300 F) or the pressure (3000–4000 psi) used for molding Bakelite or Lucite.

When edges must be sharp for microscopic study, filler sheets of a metal of similar hardness to the sample are used as a means of protecting edges during grinding and polishing. It is advisable to electroplate such samples with copper, nickel, or chrome before mounting them. Clamps are used to hold large samples or thin sections which cannot be molded, making it easier to polish them and retain sharp edges.

3.8 SAMPLE POLISHING

The polishing procedure generally consists of rough grinding, intermediate grinding, rough polishing, and fine polishing. The first step is carried out on an emery-belt surfacer or similar grinder to remove deep cut-off marks. The intermediate grinding is done with fine emery or silicon-carbide papers, decreasing in grit size in three to four stages to remove grinding marks. Each succeeding paper will produce a finer scratch on the surface of the material. During this grinding procedure, care must be taken to keep emery papers free of dust or dirt because such particles, being relatively large, will cause deep scratches to appear on the polished surface. The grinding procedure may be done by hand or mechanically, using rotating discs. When soft materials, such as aluminum and zinc, are to be polished, a mixture of kerosene and paraffin is used on the emery papers to prevent the embedding of dirt and emery particles in the metal, and also to prevent gumming or smearing of the metal surface.

Fine polishing is usually done on cloth-covered rotating discs, using fine abrasive powders suspended in a water solution. The procedure ordinarily involves two steps. A suspension of alundum equivalent to approximately no. 600 on a hard cloth, such as airplane wing cloth, canvas, or silk cloth is used first, followed by polishing with a suspension of a finer alumina powder or a magnesium oxide paste on a short-napped cloth. A small amount of pure soap solution is added to the polishing mediums as a lubricant to help keep the samples from grabbing on the polishing cloths.

Some metals, such as zinc and aluminum, require **careful control**

of the pH * of the polishing suspension to avoid etching and pitting during polishing. Soap must not be used in polishing aluminum as it tends to pit the surface.

There are several alternatives in the fine-polishing procedure. Wax wheels, wax-impregnated cloths, lead laps, or the electrolytic-polishing procedure may be used in place of the cloth-covered discs. These polishing aids tend to retain inclusions, such as graphite flakes and oxides, more readily, and cause less metal distortion at the polished surface. Extra hard carbide steels are best polished using grades of diamond paste in place of the aluminas.

Some very soft materials, such as lead, are prepared by cutting with a *microtome* instead of grinding. The microtome, a precision instrument with a heavy razorlike blade, permits very thin skins of the metal to be sliced with a minimum of surface distortion.

The polishing operation leaves the specimen with a flat, scratch-free, mirrorlike finish. Under the microscope it will show merely a mirror reflection of the light source. Inclusions or cavities present in the surface of the specimen will be distinguishable because they reflect light differently than the polished surface.

3.9 SAMPLE ETCHING

The polished surface of a specimen is etched with a suitable reagent in order to distinguish individual grains. This is usually done by swabbing or immersing the sample in the selected reagent a designated length of time. The etching time is dependent upon the type of material and its treatment.

Some metals are passive to this method of etching and must be etched electrolytically. An electrolytic etch is carried out by passing a weak d-c current through a selected reagent or electrolyte, wherein the material to be etched is the anode, and a platinum wire or simliar insoluble material is the cathode.

Microscopic Examinations

3.10 OPTICAL MICROSCOPE

The reagents used in etching attack the grains more rapidly in some crystalline directions than in others. The orientation of the grain with respect to the polished surface will, therefore, result in a different degree of etching.

* See Chapter 5.

The etched surface of a polished flat sample of pure metal may have different "levels" for grains of different orientations, somewhat as illustrated in Fig. 3.3a. An alloy may also have the surface of the grains "roughened," as illustrated in Fig. 3.3b. A reagent may be chosen that will attack the grain boundaries more rapidly than the interior of the grain. By controlling the degree of attack, tiny "valleys" may be produced at the grain boundaries before the grains are appreciably affected, as illustrated in Fig. 3.3c.
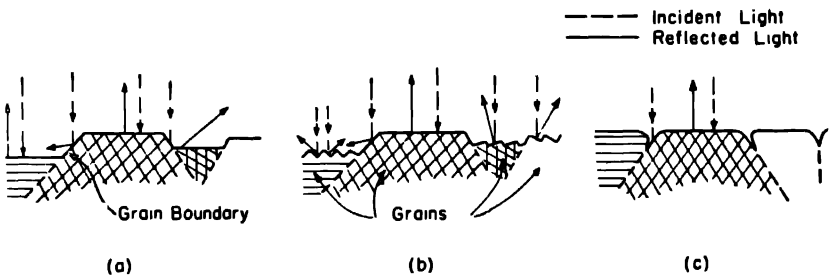

FIG. 3.3 Sketch showing the effects that may result from etching a polished surface and the manner in which the etched material reflects direct illumination. (a) Grains attacked at different rates, grain surface optically flat. (b) Grains attacked at different rates, grain surface optically rough. (c) Grain boundaries attacked, grains almost unaffected.

The grain boundaries may be detected on any of these surfaces when the sample is viewed with the optical microscope. This may be explained as follows. The light from the microscope is directed perpendicularly to the surface of the sample. If the etchant has produced a surface such as that shown in Fig. 3.3a, the light striking each grain will be reflected back into the microscope at nearly full intensity, and the grains will be uniformly bright. The grain boundaries will be dark by contrast, because the light striking them will be reflected outside the microscope. The photomicrograph, Fig. 3.4, shows the grain structure at high magnification of a pure metal etched in this way.

If the surface is like that shown in Fig. 3.3b, in which the surfaces of the grains are not optically flat, the grain boundaries will appear dark, as before, but the grains will have different shades from bright to dark. The difference in shade of these grains is due to the relative amount of light that is reflected outside the microscope by the tiny roughened planes on the exposed surface of each grain (see Fig. 3.5).

The separate grains of a surface like the one shown in Fig. 3.3c will appear uniformly bright because they are lightly etched. The grain boundaries will appear dark by contrast because the light striking
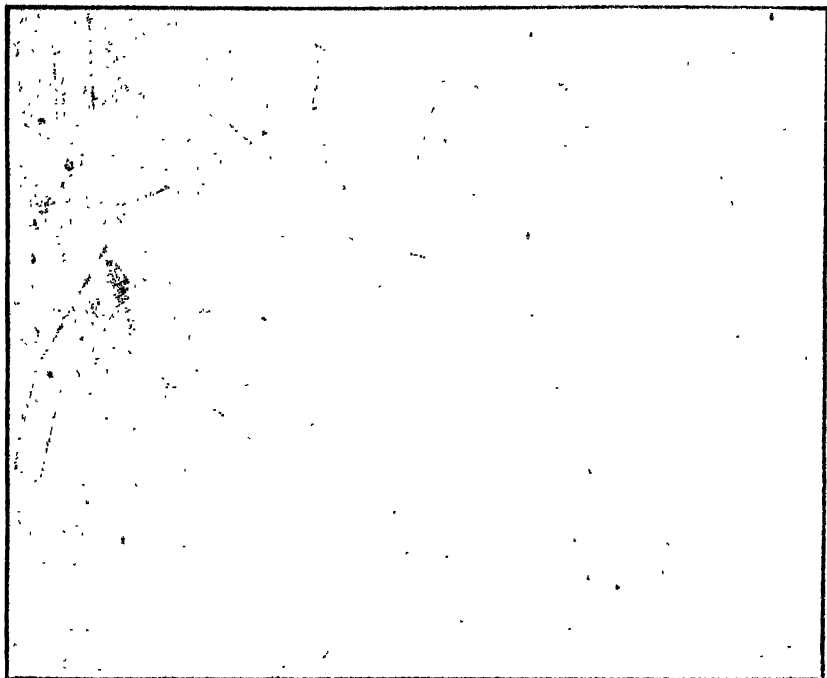
FIG. 3.4. Photomicrograph of pure nickel at approximately ×100. Black lines indicate grain boundaries, dots are impurities.

them will be partially absorbed (as a result of multiple reflections) in the tiny "valleys," and partially reflected outside the microscope (see Fig. 3.6).

3.11 ILLUMINATION FOR OPTICAL MICROSCOPES

It is customary to use an incandescent lamp as a light source in microscopes when studying metallic structures. The light is directed perpendicularly to the plane of the sample with a prism or plane glass reflector, and the reflection from the sample passes in the reverse direction to the eyepiece. This arrangement is known as *bright-field* or *direct* illumination, and the structure is discerned as described in paragraph 3.10.

Two other types of illumination are occasionally used. They are *dark-field* illumination and *polarized* illumination.

The lens system for dark-field illumination is arranged so that the incident incandescent light intersects the plane of the sample at an oblique angle. In addition, only a small fraction of the light reflected from the sample is permitted to pass perpendicularly to the

FIG. 3.5. Photomicrograph of brass (×75). Shading of grains is due to differences in orientation.

eyepiece. Greater contrast and greater detail (or resolution) can be obtained with this arrangement, and structures are visible more nearly in their true colors. The oblique illumination striking optically flat grains is not reflected to the eyepiece, however, and the relative darkness of grains and grain boundaries is the opposite of that described in the previous section (see Fig. 3.7a and b).

A somewhat similar result is achieved with polarized illumination, since only those rays suitably redirected by reflection from the sample will pass to the eyepiece. Note in Fig. 3.8b how polarized light brings out grain boundaries on a sample of cast nickel-silicon steel alloy which were obscured by coring evident from bright-field illumination (Fig. 3.8a).

FIG. 3.6. Photomicrograph of 18–8 stainless steel. Black lines are grain boundaries in which carbides have precipitated and were subsequently removed by etching.

3.12 ELECTRON MICROSCOPE

The electron microscope is a development in microscopy that has proved useful in microscopic studies of metals. This microscope's principle depends on relative electron absorption during transmission through a sample under study. Since electrons will not penetrate metal thicker than 1 μ, the examination is made with thin plastic replicas of the subject metal surface. The replica is cast on the metal surface, taking its contour on the contact side and remaining flat on the free side. After the replica solidifies, it is stripped off, supported on a 200-mesh screen, and placed in the electron beam. The electrons passing through the replica are diverged for magnification by either electromagnetic or electrostatic means, and finally fall on a fluorescent screen. The different levels produced by etching the metal result in differences in replica thickness, and these are detectable on the screen by the differences in corresponding intensity. The electrons may also fall on and expose a sensitized plate, pro-

ducing a photographic image called an *electronmicrograph* (see Fig.
3.9b). It is possible to produce these electronmicrographs up to
50,000 magnifications, although the customary range is 5000 to 20,000.
The high resolving power and the great depth of focus of this instru-
ment make it an interesting and valuable metallurgical research tool.

<center>(a)   (b)</center>
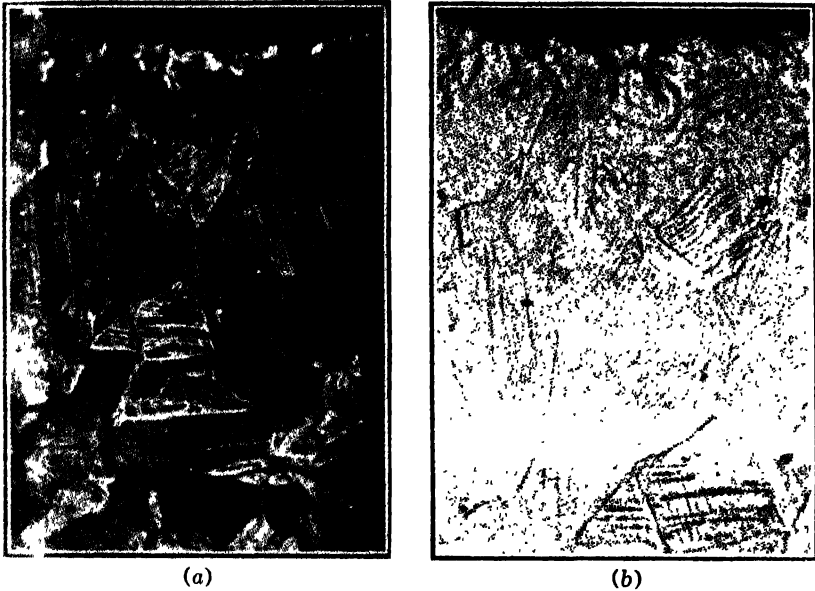
Fig. 3.7. Photomicrographs of bronze under bright- and dark-field illumination.
Note reversal of light and dark areas. (a) Dark-field illumination (×300).
(b) Bright-field illumination (×500).

3.13 CONCLUSION

This chapter has covered the typical applications for micrographic
analysis, the method of preparing samples, and some of the funda-
mentals of metallographic examination. These have been reviewed
to illustrate the possibilities of metallography as a diagnostic tool.

Although the analysis of structures is a science, the preparation of
metal for study, in particular its polishing and etching, is an art.
Problems requiring examination of structures are therefore normally
referred to the metallurgist and metallographer.

Special emphasis has been placed on selection of samples, because
the engineer is frequently called upon to obtain representative and
unaffected samples for their review by the metallurgist. It is also

(a)

(b)

Fig. 3.8. Photomicrographs of cast nickel-silicon steel alloy under bright-field and polarized illumination. Note how latter brings out silicates at grain boundaries. (a) Bright-field illumination ($\times$75). (b) Polarized illumination ($\times$75).

(a)
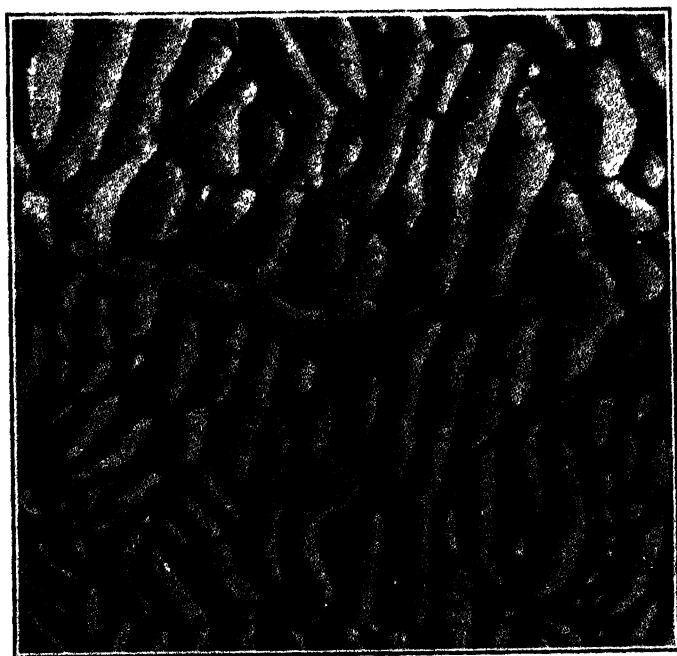
(b)

FIG. 3.9. High-carbon 1.1 per cent C steel photomicrograph and electron micrograph. (a) Photomicrograph ($\times$1000). Lamellar areas are pearlite; dark areas are unresolved pearlite. Light regions are excess cementite. (b) Electron micrograph ($\times$10,000). Light regions are cementite. Area shows pearlite with excess cementite.

important that the engineer furnish metallurgical history of the sample, because of its importance to correct interpretation of the structures.

Review Questions

1. Define the term "metallography."

2. Name and describe five characteristics or properties of metals that can be detected through metallographic examination. Distinguish whether macroscopic or microscopic examination is required for each.

3. Describe the mechanism by which etching produces contrast between various structures as viewed under a bright field microscope.

4. How are samples obtained for examination, and how are they prepared?

5. Name three types of illumination used with microscopes for specific purposes.

6. What is a microtome, and for what metals is it used?

7. How are electronmicrographs obtained?

4 MECHANICAL PROPERTIES

OF METALS

4.1 INTRODUCTION

Those properties that define the behavior of a material under applied forces or loads are broadly classed as *mechanical properties*. They are a measure of the strength and lasting characteristics of a material in service, and are of great importance to the design engineer, who must provide adequate life and performance in machines and structures.

The only criterion for suitability of a material is that it shall perform as desired in service. Service is intended in the broad sense, and includes the loads and conditions of fabrication processes, shipment, installation, and maintenance, besides actual use of the fabricated product. Often the latter is the most severe, but it may not be so, and the material and its form must be selected to perform properly under all these conditions.

The mechanical properties required in material to withstand the extremes of the many service conditions to which it will be subjected are best assured by observing the finished parts in actual use. Even then the adequacy of the properties provided must be estimated in a qualitative rather than a quantitative way. Some measure of assurance can be gained by conducting product tests under overloads, when this is possible. Otherwise, a choice of material and form can only be based on materials known to be satisfactory under similar conditions in other applications, or on simulated service tests of typical components.

The use of metals by industry has seen a companion development of laboratory tests on prepared material specimens under standardized conditions. The properties measured in these laboratory tests are those normally thought of as the mechanical properties. The engineer should recognize that they indicate only the performance of material prepared and tested in a particular fashion, which, in general,

will not parallel the fabrication or service of the actual product components. Such tests provide information which is useful for:

(a) Establishing the "quality" of material, through its conformance to specifications, as similar to other material found to be satisfactory in service.

(b) Manufacturing control of metal production and fabrication.

(c) Application in design calculations and in setting design values.

(d) Development and evaluation of new alloys.

Each of the tests normally performed in the laboratory as a measure of mechanical properties is discussed below under one of three arbitrary classes of loading. They are *static, cyclic,* and *impact* loads. Specific reference is made only to metals,* but a number of the properties discussed will, of course, apply to nonmetallic materials also.

Static Loads

4.2   STRESS AND STRAIN

When a static load is applied to a machine part or assembly, that load produces reaction forces throughout the part. These forces transmit the load through the part to the supports. The intensity of the reaction force at any point in the part is called the *stress*. Sometimes it is helpful to visualize the stress as the force per unit area exerted between the material on one side of an imaginary plane of separation in the part and the material on the other side. When the forces are parallel to the imaginary plane at the point, the stress is called *shear stress;* for forces perpendicular to the plane the stress is called *compressive stress* or *tensile stress,* depending on whether it tends to bring the material in *closer* contact or to *separate* it. Stress and unit stress are used interchangeably to mean force per unit area, and are usually expressed in pounds per sq in.

To test the behavior of materials under each of these types of stress, sample specimens are chosen of such shape that the distribution of the reaction forces, and therefore the stress, is known. Fig. 4.1 shows sketches of the common test specimens. In tension, compression, and shear tests (top row of Fig. 4.1), the stress is assumed to be uniformly distributed over the cross section perpendicular to the load.

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* The term *metal,* in the scientific sense, means only pure metals and does not cover alloys. In a commercial sense, however, it means both metals and alloys. In this and succeeding chapters the term will be assumed to have the latter meaning.

The stress in the bending and torsion tests is not uniformly distributed, but its variation can be predicted from the theory of elasticity and is given by the expressions on the figure.

Tension

S_T = Tensile stress = P/A
P = Load
A = Cross sectional area
of specimen

Compression

S_c = Compressive stress = P/A
P = Load
A = Cross sectional area
of specimen

Shear

S_s = Shear stress = $P/2A$
P = Load
A = Cross sectional area
of specimen

Bending

S = Tensile stress (tension or
compression depending on
value of c) = Mc/I
M = Bending moment, lb-in
c = Distance from neutral axis
I = Moment of inertia of
specimen = $bh^3/12$

Torsion

S_s = Shear stress = Tr/J
T = Torque, lb-in
r = Radius from neutral axis
J = Polar moment of inertia
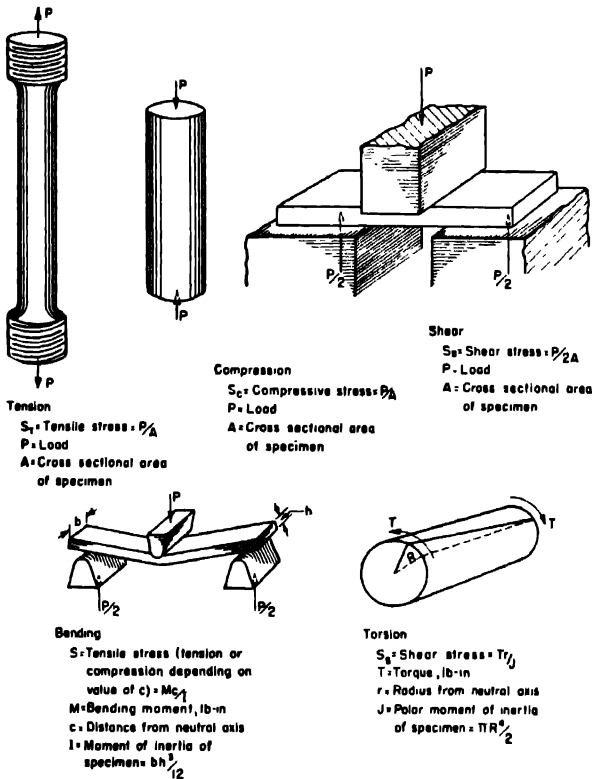of specimen = $\pi R^4/2$

Fig. 4.1. Sketches of the common test specimens. The stress distribution in each is given by the accompanying equations.

When a part is loaded, and supports stress, it is deformed or strained from its original unstrained dimensions. The amount of strain in any direction depends upon the magnitude and duration of the stress, and upon the condition of the material. *Strain* and *unit strain* are used synonymously to indicate the deformation per unit dimension. They are measured in a dimensionless unit such as in. per in., or in percentage. The strains resulting from the loads applied to the test specimens mentioned above are shown in Fig. 4.2. The strain produced by uniaxial tension is known as *elongation*.
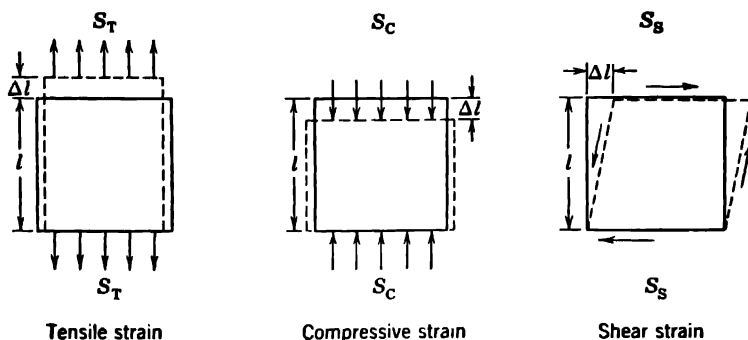
<table>
<tr><td>Tensile strain</td><td>Compressive strain</td><td>Shear strain</td></tr>
</table>

Fig. 4.2. Strains, $\Delta l/l$, resulting from three types of stress. Solid line denotes unloaded shape; dotted line is the loaded shape.

4.3   STRESS-STRAIN CURVES

In these static-load tests a gradually increasing load is applied to the specimen, and the strain in the direction of loading is periodically measured until failure is approached. The stress is calculated from the loads and the original dimensions of the specimen, and this stress is plotted graphically with respect to its corresponding strain. The resulting graph is called a *stress-strain curve*. Tensile stress-strain curves for two different metals are illustrated in Figs. 4.3 and
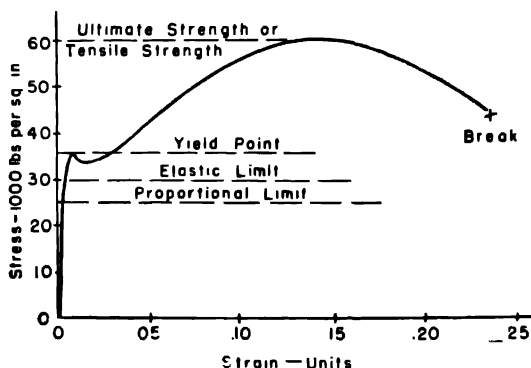
Fig. 4.3. Stress-strain curve for 0.30 carbon steel loaded in tension. Mild steels and wrought iron have this type of curve.

4.4.   Fig. 4.5 illustrates both tensile and compressive stress-strain curves. These tests are referred to as *short-time* tests because the period of loading normally does not exceed ½ hr.

The fracture or break in a tension test is usually accompanied by a "necking down" or reduction in cross-sectional area of the test bar

at the point where the fracture occurs. Since the load applied produces stress that is distributed over this reduced cross section, the maximum stress supported should be calculated from the load and the area of the minimum cross section. It is customary, however, to use the original dimensions when calculating stress, because of the difficulty and danger to equipment of remeasuring continually the actual area during test. This method of calculating the stress accounts for the droop in the tensile stress-strain curves, Figs. 4.3 and 4.4, since the true stress (based on actual area) required to cause
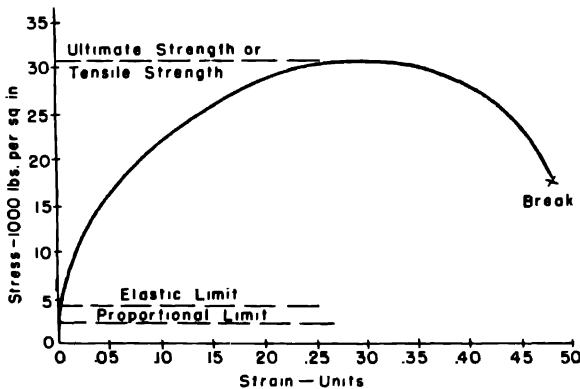

FIG. 4.4. Stress-strain curve for annealed copper loaded in tension.

failure increases to the point of fracture. The stresses for compression and shear tests are also calculated on the original dimensions, causing the stress plotted on their stress-strain curves to exceed the true stress.

4.4 STRENGTH

Stress-strain curves are a measure of the strength of a material—the capacity of the material to support a load. The various strength properties taken from these curves are as follows.

Proportional Limit. As long as the stress-strain curve is straight from the zero point (origin), strain is proportional to stress and *Hooke's law* of proportionality between strain and stress applies. The value of stress at which the curve first bends to the right is termed the *proportional limit.* The proportional limit is high for steels and low for cast iron, copper, and aluminum (see Figs. 4.3, 4.4, and 4.5).

Elastic Limit. The *elastic limit* is the maximum stress that can be applied to a metal without causing plastic deformation that will re-

main after the load is relaxed to zero. The stress-strain curve does not show the elastic limit; it can only be found by successive loading and unloading of the test specimen. For ductile metals the elastic limit is normally just above the proportional limit but close enough that they are often considered as having the same value. Cast iron,
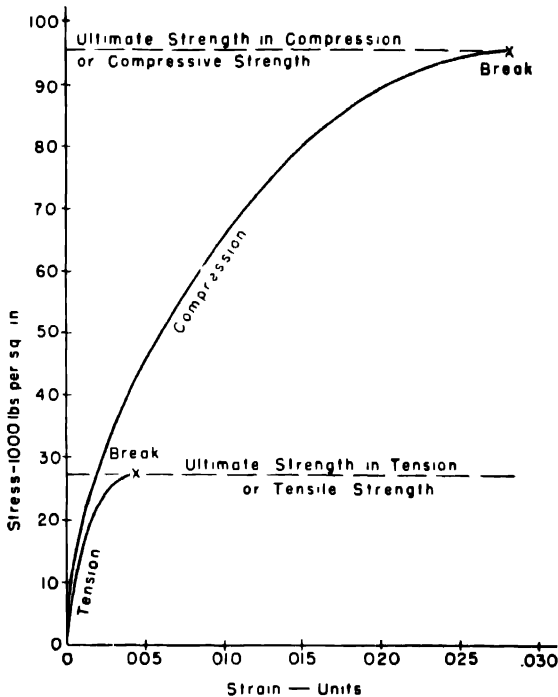
Fig. 4.5. Stress-strain curves for cast iron loaded in tension and compression.

by contrast, has an elastic limit that is well above its low proportional limit and approaches the limit of its strength. For this reason, cast iron can be given little permanent set before rupture will occur.

Successively lower values of elastic limit have been determined for most metals as the sensitivity of strain-measuring devices has been improved. This may indicate that metals have no absolute elasticity during the first loading cycle. Or it may suggest that a minute amount of set remaining in the material is recovered only after a period longer than the testing time. For practical purposes, however, the elastic limit based on observable permanent deformation in the customary testing procedure is a useful concept.

Permanent Set. When a metal remains deformed from its original dimensions after forces applied to it have been reduced to zero, it is said to have undergone plastic deformation, and the amount of deformation is called the *permanent set.* The mechanism by which the deformation takes place is characteristic of the metal as described in Chapter 1.

Yield Point. At a certain stress, called the *yield point,* low-carbon and annealed medium-carbon steels begin to slip rapidly along atomic planes and a relatively large permanent set takes place with no increase (sometimes with a decrease) in load. This point is indicated by a slight reversed curve or "knee" in the stress-strain curve (see Fig. 4.3). It occurs by propagation of slip in the initial grain to two or more adjacent grains, and cataclysmic repetition of this process in neighboring grains produces, finally, a great deal of strain. The yielding is halted when the deformation requires a higher load to proceed. Thereafter, for strain hardening to be effected, further slip on the average does not propagate to more than one adjacent grain.

Yield Strength. Hard steels, nonferrous metals such as copper, and brittle materials such as cast iron show no yield point, or "knee." To assign to these metals some measure of their deformation, the property called *yield strength* (sometimes *proof stress*) is used. A permissible permanent set is chosen, and the stress which will cause this value of set is defined as the yield strength. The significance of yield strength may be seen from Fig. 4.6, in which OPY is the stress-strain curve. If the metal is stressed to a point Y on the curve and then the load is removed slowly, the stress-strain characteristic will follow the line YX, which is very nearly parallel to OP. When the stress is zero, the metal will have recovered elastically by an amount ZX, but will retain a permanent set OX. Stress ZY is therefore the yield strength of the metal at set OX.

When the stress-strain curve is available, the yield strength may be determined by the "offset method." The permissible set, for example OX, is laid off on the strain axis, and a line drawn through X parallel to OP. The line will intersect the curve at some point Y, and ZY is the yield strength. It should be noted that a numerical value for yield strength is not significant unless the offset is specified. It has become standard practice to use the 0.5, 0.75, or 1 per cent yield strengths for copper-base alloys, and 0.2 per cent yield strength for aluminum- and magnesium-base alloys.

Ultimate Strength. The maximum stress that any metal will with-stand before fracture is called its *ultimate strength.* The terms "ten-sile strength," "compressive strength," or "shear strength" are also used, depending on which type of stress is established. The ultimate
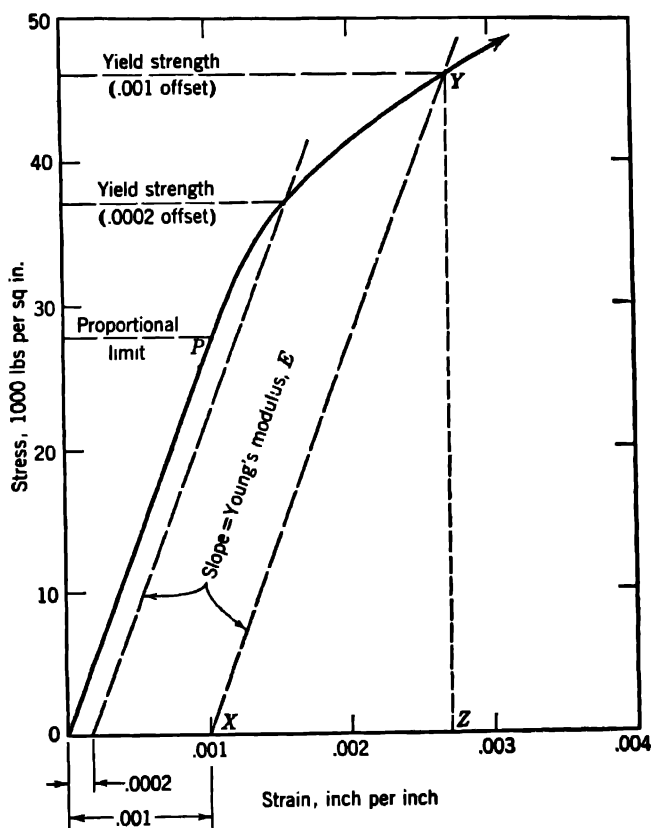
FIG. 4.6. Lower portion of stress-strain curve for 18–8 stainless steel. The offset method for determining yield strength is indicated.

strength is the highest stress which the stress-strain curve reaches. It is the stress at rupture for brittle metals and for ductile metals in compression and shear tests (Fig. 4.5), but is *not* the stress at rupture for ductile metals in tension (Figs. 4.3 and 4.4) for which the stress-strain curve has a droop preceding rupture.

Modulus of Rupture. The *modulus of rupture* is a fictitious stress calculated for either bending or torsion tests on the basis of the load causing failure, and the assumption that the elastic equation for

stress applies up to the point of failure. In the bending test, also called "traverse test," the bending moment M at failure is substituted in the flexure equation, $S = Mc/I$ (see Fig. 4.1), and the tensile or compressive stress calculated for the extreme fibers of the beam is the modulus of rupture. Similarly, for torsion the modulus is the fictitious shear stress at the surface of a cylinder computed from $S_s = Tr/J$, where T is the twisting moment that causes rupture. These tests are used mainly for brittle materials like cast iron and tile.

4.5 STIFFNESS

The resistance of a metal to elastic deformation is called its *stiffness*. Since the deflections produced in many products by operating loads may affect the workability of the components, the stiffness of the material is often a limiting design factor.

Peculiarly enough, the stiffness of a metal is varied very little by alloying with other elements. If a steel beam sags too much under load, nothing will be gained by changing to a stronger alloy steel. The strength will be increased, but if the load is the same, the beam will still sag about the same amount. The remedy is to increase the cross section of the beam.

The stiffness of a metal is measured by the moduli of elasticity in tension, compression, and shear, by Poisson's ratio, and by the bulk modulus of elasticity.

Modulus of Elasticity in Tension and Compression. The modulus of elasticity is a measure of the elastic deformation of a metal when stressed in tension or compression within the proportional limit. Its value is equal to the ratio of stress to strain, and corresponds to the initial slope of the stress-strain curve. Referring to Fig. 4.2, a and b, the modulus of elasticity, also called "Young's modulus," is

$$E = S_t/\Delta l/l \qquad \text{or} \qquad E = S_c/\Delta l/l$$

where S_t and S_c are the tensile and compressive stress, and $\Delta l/l$ is the strain caused by each stress. Because strain is a dimensionless quantity, the Young's modulus, E, has the same dimensions as stress, usually lb per sq in.

Young's modulus for steels at room temperature, regardless of treatment, alloying, or metallurgy, is between 27 and 30 million lb per sq in. For all gray cast iron it is between 14 and 18 million lb per sq in., for copper and its alloys, 14 to 17 million lb per sq in.; and for all aluminums, about 8 to 10 million lb per sq in.

Short columns under compression are often designed to operate at stresses well above the proportional limit. Their deflection is obtained from the compression stress-strain curve for the material at the design stress, and their stiffness under load from the tangent to the stress-strain curve at this stress. The stiffness determined in this way is known as the *tangent modulus*.

Modulus of Elasticity in Shear. This number is of the same nature as Young's modulus except that it refers to the ratio of shearing stress to shearing strain. It is also known as the "modulus of rigidity," or "shear modulus," and is denoted by G. Referring to Fig. 4.2c, its value is

$$G = \frac{S_s}{\Delta l/l}$$

where S_s is the shearing stress, and $\Delta l/l$ is the strain caused by S_s. For homogeneous, resilient materials (capable of storing elastic energy), G is equal to $0.4 E$, and most metals have a relationship very near to this.

Poisson's Ratio. When a metal is subjected to a longitudinal tensile stress, it will elongate and, in an attempt to retain its original volume, will also decrease in cross section. If the stress were compressive, longitudinal shortening would be accompanied by an increase in the cross section. The ratio of the strain in a lateral direction to the longitudinal strain under the conditions of uniform and uniaxial stress within the proportional limit is known as "Poisson's ratio." It is denoted by μ (mu), although sometimes the symbols σ (sigma) or $1/m$ are used. Poisson's ratio is related to the other moduli by the equation

$$\mu = \frac{E}{2G} - 1$$

and is between 0.25 and 0.33 for most metals. If the volume remained constant, μ would be 0.50; therefore the volume of most metals increases slightly when loaded in uniaxial tension and decreases when loaded in uniaxial compression.

Bulk Modulus of Elasticity. This modulus is the ratio of a uniform, triaxial (equal in all directions) tensile or compressive stress to the change in volume it produces. It is not of particular importance, because this type of loading is seldom encountered.

4.6 DISCUSSION OF STATIC STRENGTH AND STIFFNESS

Strength and stiffness, as described above, are characteristics of materials. The former is a measure of the static load-carrying capacity; the latter a measure of deformation per unit of loading. These characteristics are often confused in design practice, perhaps because the same terms are used to describe characteristics of finished parts. A part which lacks static strength fails to withstand its required load without permanent set or fracture. It may be strengthened by using a stronger material, if available, or by changing the part form to reduce stress and unit strain. A part that lacks stiffness has excessive elastic deflection under the required load. It may be stiffened by use of stiffer materials (higher E and G), if available, or by changes in part form and support to obtain lower cumulative deflection. The form of the part and the manner of loading thus influence both the strength and stiffness of the part, whereas strength and stiffness of material are inherent with a material and its condition. Design of a spring is a good example involving related strength and stiffness of part and material.

Stress-strain curves for three ductile materials in tension and compression are compared in Fig. 4.7. The Young's modulus is the same for both tension and compression, but values of elastic limit and yield strength or point in compression are about 110 to 115 per cent of their values in tension. Note that no fracture accompanies the compression tests. A limit of strain is often set for ultimate strength in compression, since ductile materials can often be loaded until the original test cylinders are flattened into plates.

The ratio of yield-point stress to tensile strength of a metal is termed the *elastic ratio*. It ranges from 50 to 65 per cent for low carbon steels, and may be raised to 75 per cent and above by cold working, or by the addition of certain alloying elements and proper heat treatment.

Data on static stress-strain characteristics in shear are difficult to find but may be estimated from other available data. The modulus of rigidity for resilient metals is about 40 per cent of Young's modulus, and the ultimate strength in shear, expressed as a percentage of tensile ultimate strength, is roughly as follows:

Material	$\dfrac{Ultimate\ shear\ strength}{Ultimate\ tensile\ strength} \times 100$
Aluminum	60%
Steel	75
Copper	90
Malleable iron	90
Cast iron	130

Alloying, as mentioned in Chapter 2, increases strength and decreases elongation at fracture (see Fig. 4.8). Cold working also increases strength and decreases elongation (Fig. 4.9), whereas annealing gives lowest strength and maximum elongation.

Grain-Size Effect. Grain size of metals has an important influence on their mechanical properties, especially for metals that obtain maximum strength by heat treating. Fig. 4.10a illustrates the effect of grain size on modulus of rupture in bending, and Fig. 4.10b on tensile strength and impact strength for heat-treated steels. The coarse-grained steels, which are indicated by the small grain-size numbers, have lower strength than the finer grain size. The mechanical properties of softer steels and other metals are not affected to the same degree by coarse grain size. But the advantages gained through use of fine grain are usually of enough significance so that fine grain is specified for materials that are used for structural applications. Besides higher strength, fine grain also results in better resistance to cracking and better machine finish, is better for deep drawing, and has somewhat improved plastic deformation as compared with coarse grain of the same composition.

Coarse-grained steels possess advantages over fine grain size in hardenability, to be discussed in Chapter 7, in forgeability, and in high-temperature creep strength.

Tests upon single crystals of metal show that the properties vary with the direction of loading. In iron, for instance, the modulus of elasticity for three different planes has been determined as 19, 31.3, and 40.5 million lb per sq in. It is evident that for the modulus of elasticity and other properties to be equal for several pieces of the same material tested in random directions, the grains must be of random orientation, and of small size relative to the size of the part. When this is the case, the material is essentially *isotropic* (equal properties in all directions). Materials that are laminated or have been treated in such a way as to cause preferred orientation do not have equal stiffness or strength properties in all directions. They are termed *anisotropic.*

The natural tendency for the location, size, and orientation of the grains to follow a statistical distribution makes the properties them-
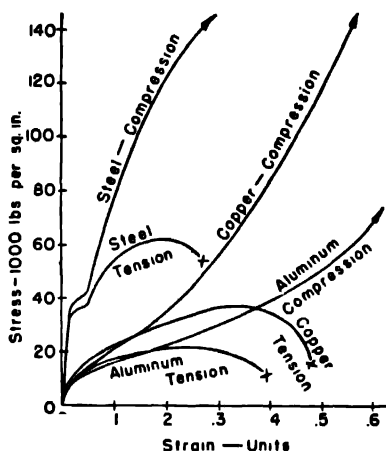
FIG. 4.7.   Stress-strain curves for three ductile metals in tension and compression.
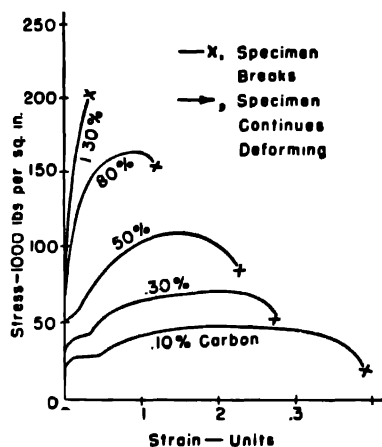
FIG. 4.8.   Effect of carbon content on the strength of annealed steel in tension.
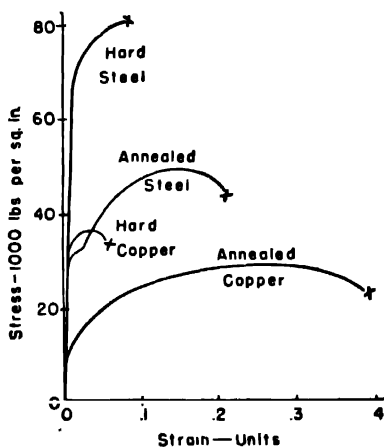
FIG. 4.9.   Effect of annealing on the strength of cold worked copper and medium carbon steel.

selves statistical in nature. That is, they show some variation due to chance causes. It should therefore be recognized that the property values reported in the literature may be several per cent higher or

lower than the properties of other pieces of the same material given the same treatments and tested in the same way.
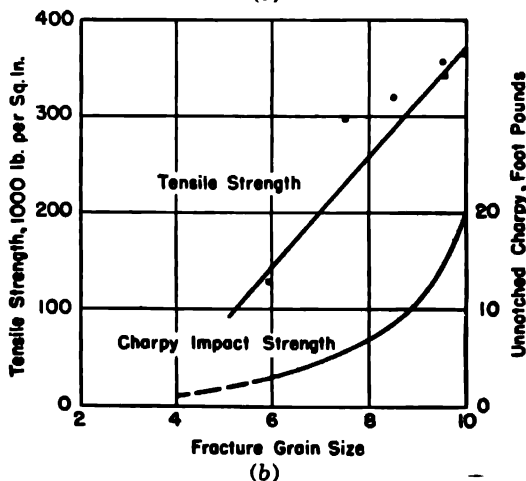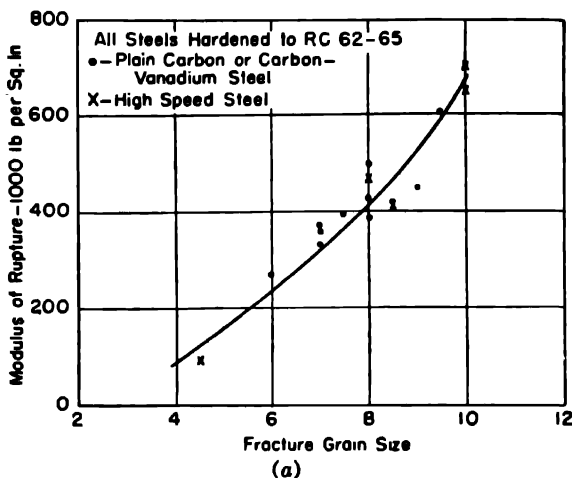
FIG. 4.10. (a) Relation between grain size and the modulus in rupture in bending for hard steels. The small fracture grain size numbers refer to large grains (N = Fracture grain size in equation: mean grains per sq. in. at $\times 100 = 2^{N-1}$).
(b) Relation between grain size and both tensile strength and Charpy impact strength for hard steels tested at 60 Rockwell C.

Mass Effect. The data reported in technical literature for strength properties of metals refer mainly to small test specimens ½ in. in diam taken from small sections. Such property data are not directly

applicable to heavy massive sections (2 to 4 in. or more thick), since these larger sections cannot be cast, worked, or heat treated at the same rates or in the same manner as the smaller sections. The difference in treatments results in differences in grain structure and size, producing substantially lower-strength properties than the same composition processed similarly in smaller sections and tested. Design of massive sections should be based on property data obtained from sections of equivalent size and treatment, when these are available.

Combined Stress Effect. If a metal part supports a combination of two or more types of stress, the magnitude of the maximum stress at failure may not be the same as if the part were in simple tension, compression, or shear. The present trend, particularly in aircraft design, toward using structural materials closer to the limit of their strength, and in more complicated members which may support many loads, makes this effect of considerable importance. Industry has begun to test materials under the action of combined stresses. This is usually done by subjecting test specimens to the simultaneous action of two or three mutually perpendicular tension or compression loads; to combinations of axial tensile stress with torsion; and to rotation of thin discs at steady speed, producing biaxial tensions. For ductile material the effect of combined tensions or combined compressions is to increase the maximum stress that causes failure; that is, to increase the maximum load that may be supported. Mixed combinations of tension and compression or shear produce additive shear stresses on oblique planes and reduce the maximum load that may be supported below loads that may be supported in simple tension, compression, or shear. Brittle materials cannot support as large loads under any combined stress combination as under simple test, but the differences are not as large as for mixed combination loads on ductile materials. Under combined loads, too, the designer should seek data applicable to the load system involved in his designs. If these are not available some assurance can be gained from application of failure theories which include effect of combined stress (see paragraph 4.33).

4.7 RESILIENCE

The ability of a material to store elastic energy without permanent deformation is termed its *resilience*. The maximum amount of elastic energy that may be so stored in the material during its first loading cycle is called *proof resilience*. It corresponds to the area under the stress-strain diagram from the origin to the elastic limit, and is ex-

pressed in energy units such as ft-lb per cu in. Materials that have high resilience are used for springs. Annealed copper would make a poor spring because its elastic limit is very low; but cold-worked copper has a much higher elastic limit and resilience, and therefore makes a better spring. Thus, high resilience is associated with high elastic strength. The resilience of different metals is often compared by bouncing a hard steel ball on each and noting the relative height of the rebounds—the more resilient metal will cause the higher bounce. The Shore scleroscope embodies this method of testing by measuring rebound of a diamond-tipped tup dropped on the specimen from a fixed height. Hollow parts, thin stock, and rough surfaces give low rebound values.

4.8 TOUGHNESS

The work per unit volume required to fracture a metal is called its *toughness,* and is equal to the total area under the stress-strain curve. It is a measure of the total energy-absorbing capacity of the metal, including both elastic and plastic deformation. Some mild steels are tougher than hard steels because the plastic deformation at fracture for the latter may be quite small. Toughness shows some relationship to impact strength, i.e., resistance to shock loads, but the energy values measured in a static test and an impact test do not agree for all metals or test conditions.

4.9 DUCTILITY, MALLEABILITY, AND BRITTLENESS

A metal that may be worked to a different size or shape without breaking or shattering is *ductile,* or *malleable.* But if only a very small change in dimensions can be made before the metal fractures, it is *brittle.* The arbitrary dividing line between them is usually placed at 5 per cent strain of a test bar at rupture, brittle materials having less and ductile or malleable materials having more than this deformation.

Although the terms ductility and malleability are frequently used interchangeably, *ductility* is more often thought of as a tensile quality, the ability of the metal to be drawn out or stretched; whereas *malleability* is considered as a compressive quality, the ability of the metal to be flattened by rolling or hammering.

The importance of ductility in a metal, as measured by the 2-in. gage-length tensile test, is often overestimated. Ductility may be needed in actual parts to (a) provide for readjustment of stress con-

centrations, or to distribute loads over a member or members, and to (b) permit cold deformation in forming or drawing.

Stress readjustment is obtained with only a small amount of ductility, usually within 1 per cent. Greater ductility is not required for this purpose, as indicated by successful operation of cast-iron crankshafts having practically zero ductility. The specification for moderate ductility in materials for members that must operate within the elastic limit with possibility of readjustment for load distribution is, thus, not directly related to design. Such a specification recognizes a characteristic ductility in a given metal at a particular strength level and processing procedure, and calls for this characteristic value, since lower ones suggest something may be wrong with the material.

If the elongation in a tensile test is plotted with respect to distance from the necked portion of a test specimen, the elongation projected to zero gage length will be almost twice that at 2 in. for ductile materials. At 100 in. it will be much less. This indicates the degree of local ductility that is available at zero gage length for stress readjustment. Elongation for the 100-in. length indicates the amount that may be considered limiting in stretcher-forming operations. Increased width, of course, reduces this amount.

Tensile drawing and forming operations are most closely related to the *uniform elongation* of the tension stress-strain curve. This elongation is given by the strain at the maximum stress point of the tensile stress-strain curve before necking begins. The permissible strain to the point of necking may be determined by the strain hardening exponent, termed m, for the metal. This exponent is the slope m of the almost straight line obtained by plotting $\log_e$ of true stress versus $\log_e$ of true strain. For steel it has been found that m values over 0.25 indicate good drawing characteristics, but values as low as 0.2 are often satisfactory where drawing is less severe. Drawing operations that involve biaxial tensile stress reduce the available uniform elongation indicated from simple tension test. A flat-topped stress-strain curve also indicates instability in forming which may induce buckled uncontrolled sections.

Other methods for specifying formability are:

(a) Ability to draw standardized cups (Erichsen * test).

(b) Ability to draw flanges from sheet, which indicates shrinkability (compression flange), extensibility (tension flange), and "spring back" of the metal.

· * Or modifications by Olsen, Guillery, Persoz, Avery, and Amsler.

(c) The *bend* test for wire or strip, which is a *go, no-go* test for bending these forms 90°, 180°, or several times about a given radius, or 180° upon itself.

(d) Growing in favor is the practice of specifying material ductility for forming on the basis of ability to draw to the part dimensions in the actual die.

4.10 HARDNESS

The hardness of metal is difficult to define as a distinct property because it is closely associated with metal structure, composition, and other mechanical properties. Consequently, a number of different kinds of hardness have come to be recognized. Those tests which measure resistance to indentation will be considered here, and those indicating resistance to abrasion, wear, cutting, and dynamic penetration will be considered later.

Resistance to indentation is measured by applying an indenter of a particular shape to the subject metal under a suitable static load. The hardness measured in this way is assigned a numerical value based either on the contact area of indenter and metal, the projected area of the recovered indentation, or the depth of the recovered indentation. Tests in common use are Brinell, Rockwell, Vickers, and Monotron. All are most useful for establishing quality of a metal, rather than to provide quantitative design data.

Brinell Hardness Tests. A load (for iron-base alloys 3000 kg for 10 sec, and for softer nonferrous metals 500 kg for 30 sec) is applied by a hand-operated hydraulic press to a smooth metal surface through a hardened steel ball 1 cm in diameter. The projected diameter of the remaining spherical impression is measured, and from it the surface contact area is calculated. The numerical value of the Brinell hardness is equal to the load divided by this area:

$$Bhn = \text{load (kg)/area (sq mm)}$$

There are several limitations to the standard tests:

(a) They cannot be used for very hard metals. For metal harder than about 480 Brinell number, special tests employing a tungsten carbide or a diamond ball are available.

(b) The indentation should not mark through the specimen so the minimum thickness of steel that can be tested is about 0.1 in.

(c) The test must be made far enough from the edge of the metal so that no bulge results.

(d) The edge of the indentation is not always distinct.

(e) For small specimens or very soft metals, a lighter load and smaller ball of the same P/D^2 ratio as the standard test are used.

Frequently in production-control work, the Brinell number is calculated from the depth of indentation, because depth is easier to measure than diameter. This method is not recognized as standard, however.

Rockwell Hardness Test. A standard minor load is applied to seat the indenter in the surface of the metal, and then a standard major load is applied and removed by a loaded lever system. The hardness number for the depth of indentation caused by the major load alone is indicated by an arbitrarily calibrated scale provided. The numbers increase with hardness. The indenter used may be a hardened steel ball, or a diamond cone, called a *brale,* which has a spherical apex. Choice of the indenter, as well as the major load applied, depends on the hardness of the metal to be tested. The combination should result in a nearly mid-scale indication. A letter is included with the reading to indicate the combination used, e.g., Rockwell B 100. The Rockwell B ($\frac{1}{16}$-in. diam ball and 100 kg load) and Rockwell C (brale and 150 kg load) tests are used most frequently for structural steels and hard steels respectively.

The *Rockwell superficial hardness* test is used where a very shallow impression over a very small area is desired. It employs lighter minor and major loads with either type of indenter, and a more sensitive depth measuring system. It is used for thin strip or sheet, nitrided or lightly carburized parts, finished pieces on which test marks are undesirable, areas near edges, very small parts or sections, and shapes that would collapse under the heavier loads.

Vickers Hardness Test. A load from 5 to 100 kg is applied through a square-based pyramid (136°) and removed automatically by a weight and cam mechanism. The load is chosen in relation to the hardness and thickness of the part. The hardness number, expressed *DPH,* is obtained by dividing the load in kg by the impressed area in sq mm, as determined by length of the diagonal of the impression. Theoretically, the hardness numbers are independent of the load.

Eberbach has used the Vickers indenter under spring load in place of the microscope objective. After indenting, the objective is replaced for measuring indentation of microconstituents. These are called *microhardness* tests.

The Vickers indenter is also used in the Tukon tester, which employs loads from 25 g to 50 kg and sensitive positioning and measuring equipment suited to minute hardness determinations. Hardness, as before, is indicated by calculating the *DPH* number. The *Knoop*

indenter is sometimes used with this tester. It also is a diamond pyramid but makes a rhombic indentation. With it hardness is specified as I = load, kg/projected area of indentation, sq mm.

Monotron Hardness Test. The load registered in producing an indentation of a given depth is a measure of hardness in this test. The standard depth is 0.045 mm with a 0.75 mm diamond ball. Other scales are provided for larger ball indenters of diamond or tungsten carbide.

Comparison of the hardness numbers for these tests and the approximate tensile strength for a corresponding steel are given in Table 4.1. Curiously enough, for carbon and low-alloy steels the

Table 4.1   Approximate Comparison of Hardness Numbers and Tensile Strength for Structural Steel

	Vickers, DPH	Brinell			Rockwell			Sclero-scope Hardness	Tensile Strength, ×1000 psi
		10 mm 500 kg Steel	10 mm 3000 kg Steel	10 mm 3000 kg Tungsten Carbide	B 100 kg 1/16 in. Ball	C 150 kg Brale	Superficial 15 kg Brale		
Steel	600		.	564		55.2	88	74	289
	550			517		52.3	86.6	70	264
	500		465	471		49.1	85	66	240
	450		425	425		45 3	83.2	60	214
	400		379	379		40.8	80	54	190
	350		331	331		35.5	78	48	166
	300		284	284		29.8	74.9	42	141
	250		238	238		22.2	70.6	36	116
Unhardened Steel,	175	210			95			35	101
Cast Iron, and	150	174			87.7			33	84
Most Nonferrous	125	142			77.5			29.5	..
Metals	100	115			63.5			24	..
	75	..			41				.

Adapted from *Metals Handbook*, A.S.M., Cleveland, Ohio, 1948.

Bhn multiplied by 500 is approximately equal to the tensile strength, but such a relation does not hold for highly alloyed steels, case-hardened steels, or nonferrous metals.

4.11   EFFECT OF LOW TEMPERATURES ON STATIC STRENGTH PROPERTIES

The use of metal commodities at low temperatures has spread to include most of the basic industries. Gas fractioning in the chemical

industry involves temperatures of −150 F, petroleum dewaxing involves similar temperatures, some refrigeration applications require handling of liquids at −75 F, military machinery and vehicles are often subjected to arctic climates, and aircraft for high altitudes experience temperatures of −60 F and below. Consequently, much investigation of metal properties has been undertaken at temperatures as low as −300 F. In addition, research of a basic nature is being conducted in several laboratories at temperatures near absolute zero.

In the temperature range from room temperature to −300 F there is a relative absence of metallurgical changes in most metals. Accordingly, abrupt changes in the properties as the temperature is lowered are not usually encountered. Metals generally show a continuous increase in yield strength, tensile strength, hardness, and modulus of elasticity, and a small decrease in ductility. This characteristic applies, in general, to metals having a face-centered cubic structure as found in lead, austenitic steel, and aluminum, copper, nickel, and their alloys. Although these materials have a wide variation in room-temperature toughness, their behavior is consistent and predictable at lower temperatures.

The outstanding exceptions to this general trend are the ferritic steels. Both plain carbon and low-alloy steels become embrittled at low temperatures, sometimes at temperatures as high as 200 F. Embrittlement is indicated by a loss in toughness over a narrow or a moderate temperature range, and failure is characterized by brittle coarse-grained fracture, especially as indicated in notched-bar impact tests. The temperature at which the impact energy absorption is reduced to 50 per cent of the ductile value is generally taken as the *transition temperature* for this effect. It is believed the transition is associated with metallurgical changes brought about by exposure to the low temperatures. The ferrite probably decomposes, producing some carbide. Lower carbon content and alloying elements that absorb carbon thus lower the transition temperature. Fine grain size and deoxidation of the steel also have this effect. Increased sharpness of notch, increased bar width (for ratios of notch radius to bar with less than 1.10), and higher striking velocity in the impact test all appear to cause transition at a higher temperature.

Nonferrous exceptions to the general trend are tin, tin alloys, lead solders having more than 15 per cent tin, zinc, molybdenum, tungsten, and the unstable precipitation-hardened alloys.

4.12 EFFECT OF HIGH TEMPERATURES ON STATIC STRENGTH PROPERTIES

Numerous tests have been made on metals at high temperature, because of the large number of applications (engines, turbines, boilers, furnaces, stills, etc.) that involve high-temperature service. In general, all metals suffer a loss in static strength and stiffness and have some increase in ductility as temperatures are increased above room
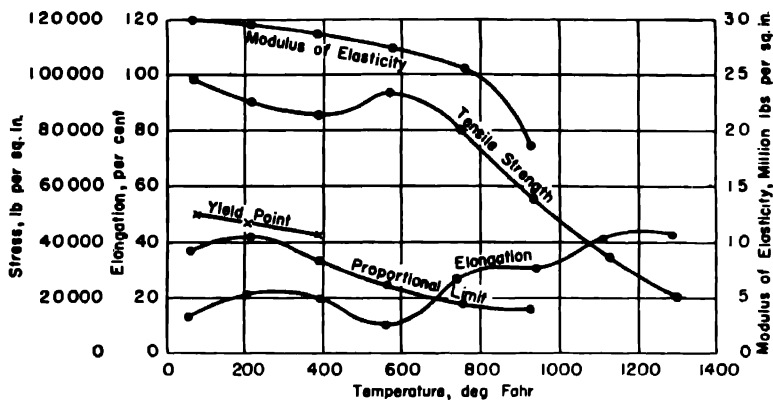

Fig. 4.11. Effect of temperature on the short-time static strength of 0.53 per cent carbon steel. *From tests by H. J. Tapsell and W. J. Clenshaw, "Properties of Metals at High Temperatures II," Engineering Special Report No. 2, Dept. of Scientific and Industrial Research, Great Britain, Sept. 1927.*

temperature. In addition, many metals undergo metallurgical changes in structure or phase at elevated temperatures, with consequent abrupt changes in mechanical properties. Steel exhibits such changes to a marked degree, and as a result there are inflections and humps in its short-time strength-vs.-temperature curves (see Fig. 4.11). The reduction in strength is large at temperatures near the recrystallization temperature, and rupture generally changes from transcrystalline to intercrystalline failure. Stiffness is reduced even more abruptly at this temperature and, for higher temperatures, the elastic modulus is difficult to interpret from stress-strain curves.

The resistance to plastic deformation is more sensitive to the rate of deformation at high than at low temperatures, and strain hardening is less. Stress-strain curves obtained at several strain rates at high temperature would appear as illustrated in Fig. 4.12. The low rates result in more deformation for a given load. Such static tests at vari-

ous rates correlate almost quantitatively with creep tests for metals
and temperatures that do not involve metallurgical changes.

Deformation is not entirely of either plastic or elastic type at high
temperatures. If a load is applied to produce a small amount of
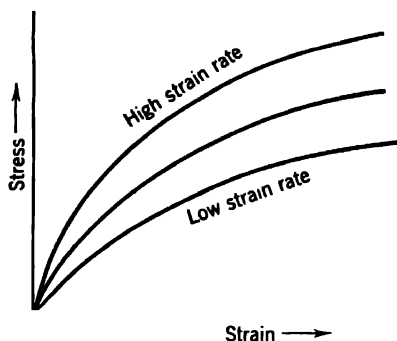
Fig. 4.12. Effect of strain rate on stress-strain curve.

strain, and then is removed, the recovery of deformation will occur
as illustrated in Fig. 4.13. Elastic deformation is recovered as the
load is removed. Some of the nonelastic deformation then recovers
over a period of time. This deformation is termed *anelastic*. It
takes place mainly in the grain boundaries of the material and is
proportional to the stress applied. It is similar to a jigsaw puzzle
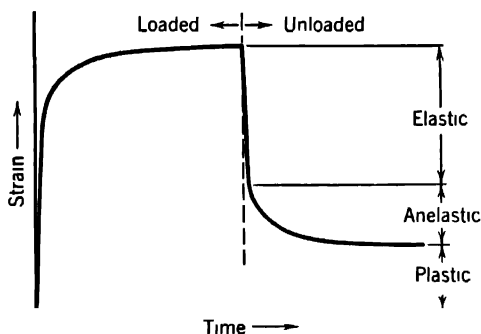
Fig. 4.13. Recovery of strain after loading to plastic range at high temperatures.

glued together with a viscous tar that takes time to stretch and time
to recover. Anelasticity appears to be intimately related to damping
capacity, to creep, and to the effect of temperature and frequency on
the elastic modulus. Effects of anelasticity become pronounced at

temperatures above 175 C in magnesium, 250 C in aluminum, 300 C in copper, 375 C in α-brass, and 425 C in α-iron.

4.13 CREEP

In 1920 Lea and others published results of tests on ferrous metals subjected to constant loads for long periods of time at elevated temperatures. The specimens were found to deform continuously during test, even though the stresses were less than the apparent yield point for a short-time test on the metal at the same temperature. This phenomenon of continuous stretching under load is the phenomenon of *creep*. It occurs even when a metal is loaded at room temperature, but in most metals the amount is not measurable nor of practical significance compared with that which occurs at elevated temperatures.

Although Lea's investigation of creep started extensive research in many countries, this study is still in its infancy and the data on the progressive failure of metals at high temperatures are as yet not very well correlated. The factors which affect creep are so numerous and complexly interrelated that it is impossible to vary just *one* and study its effect. Many changes not attributable to the stress take place during the long period of heating, thus complicating the analysis. Of the numerous theories which have been advanced, only the major concepts are discussed here.

4.14 THEORY OF CREEP

If a creep test is conducted at high enough stress or temperature, or for a long enough time, the test specimen will fracture. Between the time the load is applied to the material and the time, perhaps years later, when the fracture occurs, the material appears to pass through three rather well-defined stages of creep. These are illustrated in Fig. 4.14.

(1) *First Stage—Stress Readjustment and Strain Hardening.* Behavior in this stage appears to be influenced by anelasticity but is usually attributed to nonuniform stress distribution. Minute stress concentrations appear at irregularities in structure, for example, at grain boundaries, and, in steel, at the boundaries between ferrite and cementite, which have different elastic properties. To relieve and distribute this stress, interatomic slippage will take place wherever it most easily can, and this slippage causes distortion of the crystal lattice. If the thermal agitation does not cause realignment of the

lattice, further slippage is hindered and the metal *strain hardens.* After relief in the places most favorable to slip, slippage takes place with greater difficulty elsewhere, which accounts for the creep-vs.-time curve bending to the right (see Fig. 4.14, first stages of curves). This slippage gradually decreases stress concentrations and distributes the stress evenly throughout the metal. Sufficiently low combinations of
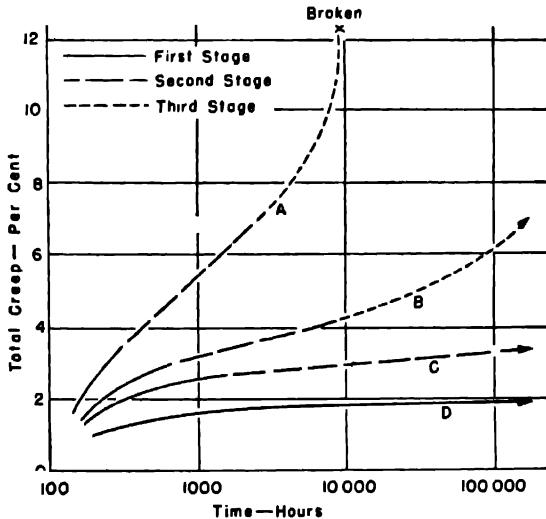
Fig. 4.14. Three stages of creep on a creep-time curve for a chrome-nickel steel. Curves *A, B, C, D* are for successively lower temperatures at the same stress, or successively lower stresses for the same temperature.

stress and temperature permit the first-stage creep to proceed throughout the entire service of a metal part (curve *D*, Fig. 4.14).

(2) *Second Stage—Strain Hardening and Annealing.* If the combination of stress and temperature is sufficiently high, annealing may, after a time, become as active as strain hardening, so that these two tendencies balance each other and creep proceeds at a constant rate. This is the second stage of creep and is indicated by the straight portions of the curves, Fig. 4.14.

(3) *Third Stage—Necking and Structural Changes.* This stage is marked by an increased deformation rate leading to fracture. Stress intensification resulting from necking of the material is the primary cause of increasing creep in this stage, but it is believed structural changes produced by strain, time, and temperature also contribute substantially.

4.15 CONSTANT-LOAD CREEP TEST

The bulk of creep data available is obtained by maintaining a standard test specimen at a constant temperature under a fixed load and observing the strain from time to time. Other specimens are tested similarly under different loads or at different temperatures. The resulting data may be summarized to show the effect of any two of the four parameters; plastic creep deformation, time, stress, and temperature.
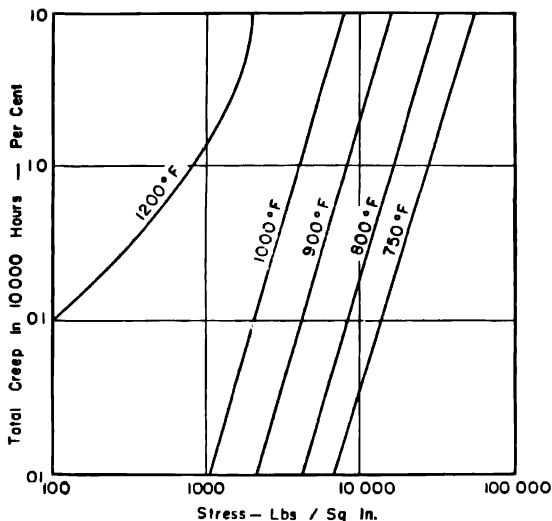
Fig. 4.15. Creep-vs.-stress curves for 0.33 per cent carbon cast steel. *From "Symposium on the Effect of Temperature on the Properties of Metals," courtesy of ASME and ASTM.*

A *creep-vs.-time diagram*, such as Fig. 4.14, is obtained by plotting creep (usually plastic strain omitting the initial elastic strain) against time for constant stress and temperature.

A *creep-vs.-stress diagram* may be obtained by cross plotting, from a creep-vs.-time curve, the creep in a given period, for example 10,000 hr (14 months), with respect to the stress which caused it (see Fig 4.15).

A *stress-vs.-temperature diagram* shows the stress which will cause a given creep or a given creep rate (second stage slope) at a given temperature (see Fig. 4.16). Diagrams of this type are obtained by plotting from a number of creep-vs.-time diagrams for different stresses and temperatures.

A *stress-vs.-time diagram* is obtained by cross plotting, from single-temperature creep-vs.-time diagrams, stress to cause a given creep or creep rate (second-stage slope) against time. Fig. 4.17 illustrates a stress-vs.-time diagram and the creep-vs.-time curve from which
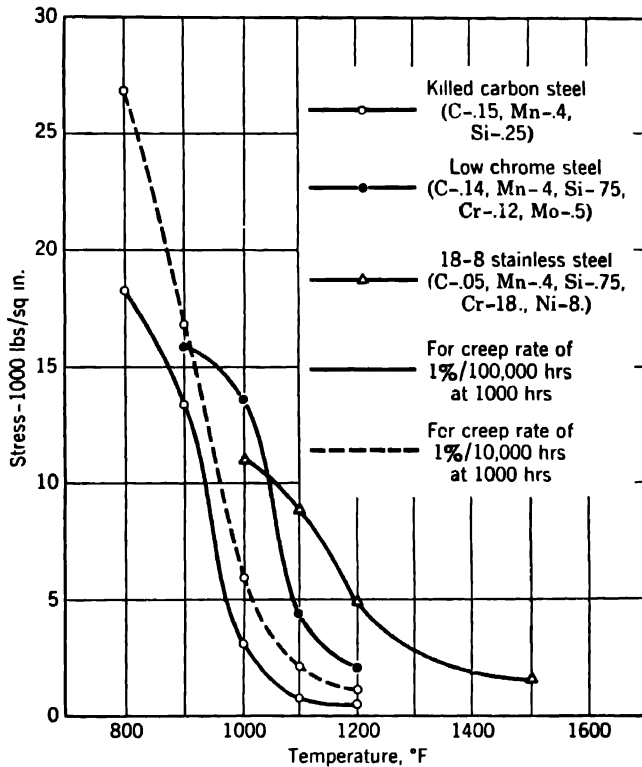
FIG. 4.16. Stress-vs.-temperature curves for three steels. Solid line is for creep rate of 1 per cent per 100,000 hr at 1000 hr. Dotted is for creep rate of 1 per cent per 10,000 hr at 1000 hr. *Data from Digest of Steels for High Temperature Service, courtesy Timken Roller Bearing Co.*

it was derived. For this steel, the 1 per cent creep curve on log-log coordinates is a straight line. Diagrams of this form are gaining favor for design application.

4.16 STRESS-RUPTURE TESTS

These tests are conducted in the same fashion as constant-load creep tests, but the loads and testing time are selected to cause failure by rupture. The time required to cause failure generally varies

with the stress in such manner that a straight line or lines can be drawn through the points plotted to log-log coordinates. Fig. 4.17 contains a rupture stress-time curve and the strain-time diagram from which it was derived. In this example the rupture curve is composed of two straight lines, the slope changing at about 160 hr.
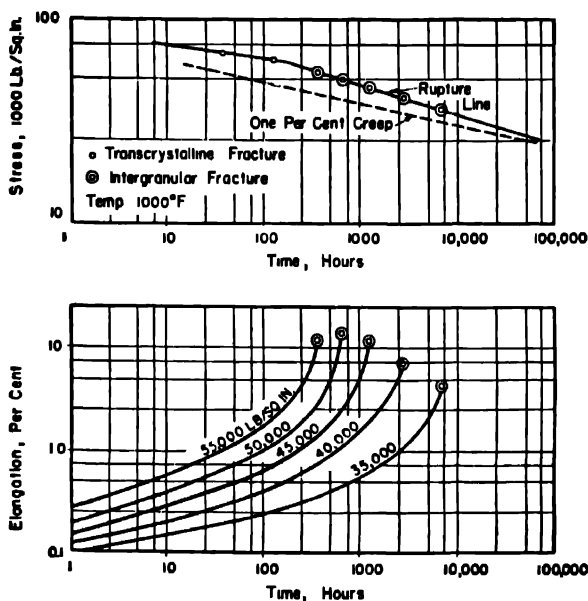
FIG. 4.17. Stress-vs.-time diagram, above, derived from creep-vs.-time diagram, below. Note change in slope of the rupture line at 160 hr.

This change takes place primarily because of a change in the mode of deformation from transcrystalline slip to grain-boundary rotation. The occurrence of the grain-boundary mechanism reduces the amount of creep strain prior to failure, since the initial slope of the rupture curve was more nearly horizontal.

Rupture data are important to design of high-temperature equipment, both for relatively short-life, highly-stressed parts such as jet engine components, and for longer life equipment like boilers and steam turbines. For the latter, for example, the 1 per cent creep line in Fig. 4.17 is very close to the rupture line at 100,000 hr. A part, such as a boiler tube, designed for 1 per cent permissible deformation under creep would be very close to breaking after 100,000 hr of use.

4.17 RELAXATION TESTS

If the loading applied to a metal part causes the total deformation (rather than the stress) to remain constant during long-time high-temperature service, the metal will be found to relax, i.e., its load-carrying ability will continuously decrease. This occurs in applications such as boiler rivets and turbine flange bolts. The bolts are drawn very tight when a turbine flange is originally assembled. Often they are heated and tightened so their contraction on cooling will give added pressure. Use of the turbine subjects the bolt to a combination of stress and high temperature that causes slippage on interatomic planes. The stress is slowly relieved and distributed, and the bolt gradually loosens or relaxes. Although the original strain in the bolt was entirely elastic, part of this elastic strain is gradually changed into plastic strain. This decreases the stress in the bolt, and the pressure between the flanges becomes less. Choice of proper allowances to provide the required pressure for the desired period requires tests showing the relaxation of the bolt material with time. Tightening the bolts during service will, of course, change the relaxation conditions, and this effect is also being studied.

The results of relaxation tests at constant strain and temperature on several steels are shown in Fig. 4.18. The remanent stress is meas-
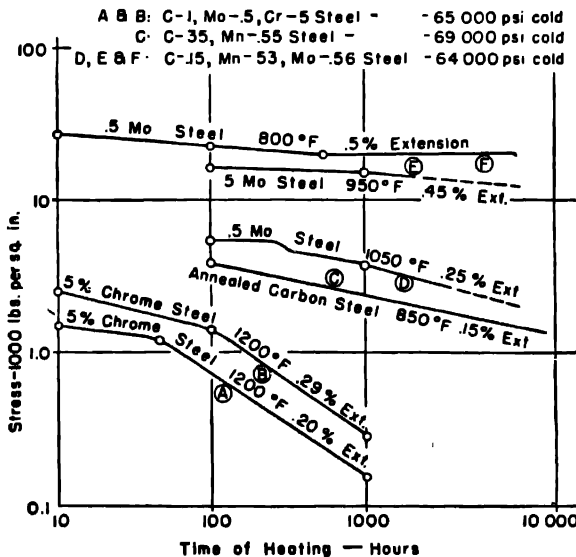

Fig. 4.18. Relaxation elastic stress-vs.-time diagram taken at constant total strain and constant temperature for three steels.

ured periodically during the test and plotted as a function of time (usually on log-log coordinates). This type of curve permits direct determination of the *original* stress required to provide a given *remanent* stress after the required duration of high-temperature service. The shape of these curves, as with constant-stress curves, depends upon whether strain hardening or annealing predominates. If the steel tends to anneal, the curve bends downward, as shown in *A*, *B*, *D*, and *E*. If the metal reaches a steady state in which strain hardening causes the relaxation to cease, the curve will bend up and become nearly level (curve *F*). In 10,000 hr at 850 F the carbon steel (curve *C*) has shown neither tendency.

4.18   CREEP SPECIFICATIONS

It is often more important for a designer to know *how much* a part will creep rather than *how fast* it will creep, but *creep rate* in the second stage is the most common way in which the creep resistance of metals is reported. *Total creep* expressed in per cent (at a given number of hours) may be of more importance where deformation must be limited. For example, the slope of curve *A*, Fig. 4.14, shows the creep rate at 1000 hr to be 1.55 per cent per 1000 hr. Nevertheless, in the first 1000 hr the total creep has actually been 5.4 per cent. It is advisable for the designer to consult data both on total creep and on creep rate when they are available. It is noted that plastic strain is customarily reported as creep. Elastic strain (and any anelastic deformation if eliminated from the creep) must be added to the creep figures to obtain the total strain. Prolonged heating may also bring about further changes in the outer dimensions through metallurgical change. This is not creep, but is superimposed upon it and increases the complexity of its study.

The long time necessary to conduct creep tests has led to searches for accelerated tests, but none have proved satisfactory. As an alternative, methods of extrapolation have been used. Extrapolations from data on tests that have not completed the first stage give excessive values of predicted creep. Extrapolations of creep curves carried well into the second stage are customarily limited to one log cycle to reduce possibility that the metal will enter the third stage of creep during long-time service. A small creep allowance (1 per cent or less) ordinarily gives adequate protection against such an occurrence. Long-time creep tests eliminate the necessity for extrapolation on the materials tested, but, unfortunately, new materials

must be judged and even applied before complete creep tests can be made.

Cyclic Loads

4.19 CYCLIC LOAD PROPERTIES

Most structures and machines are subjected to loads, and therefore stresses, which are not steady or static. Even a bridge or a building, which may be thought to be under static loading, supports loads that vary with the seasons (heat, wind, snow, rain, etc.) and with traffic. Some of the properties determined as a measure of a metal's resistance to cyclic or varying loads are mechanical hysteresis, damping capacity, endurance, wear resistance, cutting hardness, and machinability. These properties are discussed in the order named.

4.20 MECHANICAL HYSTERESIS

The stress-strain curve for a ductile steel stressed slowly enough so the reaction forces always equal the load applied will be similar to Fig. 4.19. If at A the load is decreased to zero, the stress-strain curve will follow AaA', which is nearly, but not quite, parallel to OE. When the steel is then reloaded, it will follow curve $A'bB$, which is a little to the left of AaA'. The area enclosed is called a "hysteresis loop," and is equal to the energy per unit volume transformed into heat during the stress cycle. Because of the work-hardening properties of metal, the elastic limit and yield point B on curve $A'bB$ will be slightly raised as shown. If deformation and stress are continued to point C and then relieved, a curve CcC'', similar to AaA', will result. If the metal is allowed to rest for several days at point C', it will "recover" slightly, and the yield point will be increased to D, as shown. Similar curves for copper are shown in Fig. 4.20. Note that work hardening is evidenced in it also and that it converts more energy into heat per cycle than the steel.

If the stress is completely reversed, loops as shown in Fig. 4.21 will result. LOM is the static stress-strain curve of the metal. Reversal of stress at M causes stress and strain to follow curve $MPNL$. Another complete reversal will bring the stress back to M along curve $LTUM$. This loop is much exaggerated in width—the metal would soon break if reverse-stressed so far beyond its elastic limit. OP and OT represent remanent strains (permanent sets) in the metal when the stress is reduced to zero from tension and from compression respectively. ON and OU represent "hysteresis stresses" at zero strain as a result of anelasticity and plastic flow.

Hysteresis loops are detectable in steel at reversed stresses as low as ±1500 lb per sq in. If a metal tends to anneal (e.g., lead), the loop may become larger as the loading is repeated, but in steel, the
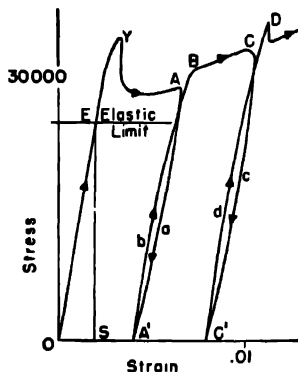
FIG. 4.19. Stress-strain curve for mild steel with reloading above yield point.
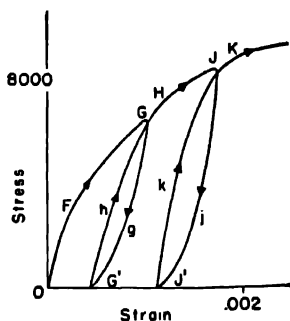
FIG. 4.20. Stress-strain curve for annealed copper with reloading.
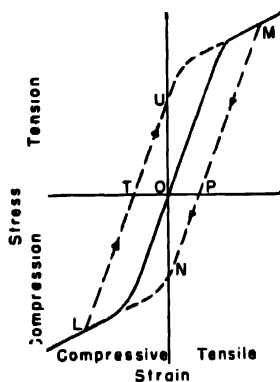
FIG. 4.21. Mechanical hysteresis loop caused by reversed cyclic load. Width of loop is exaggerated.
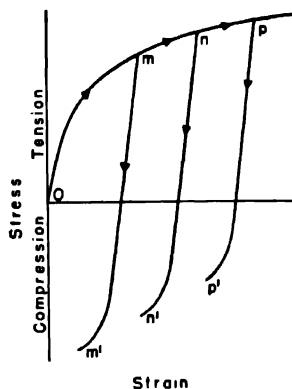
FIG. 4.22. Effect of reversing the load after stressing in tension beyond the elastic limit.

work hardening causes the loop to remain small, in spite of repetition. After a large tensile deformation such as Om, On, or Op (**Fig.** 4.22) a reversal of loading results in curves mm', nn', or pp', indicating a continuous decrease in the compressive elastic limit as greater and greater tensile stress is allowed in the load cycle.

4.21 DAMPING CAPACITY

Vibration of metal parts causes the metal to be carried through a repeated stress cycle. If the metal's hysteresis loop is large, appreciable energy will be absorbed during each cycle. The vibration will be mechanically damped. The energy removed each cycle is defined as the *damping capacity*. This characteristic is often desirable in metal and accounts for the use of cast iron (a good damper) for machine- and steam-hammer-bases and for some crackshafts. The long-continued "clang" of steel and the "ring" of hard brass and Duralumin when struck indicate that vibrations in them persist because of low damping.

Damping capacity is usually reported in terms of the *logarithmic decrement*, δ, which is the exponent in the equation $A_1/A_2 = e^{\delta}$ where A_1 is one amplitude in a free vibration of a test bar, and A_2 is the next successive smaller amplitude

Values of δ are dependent on stress, temperature, and frequency. For high-alloy steels for high-temperature service, δ increases irregularly with stress, has a minima with temperature in the neighborhood of 700 to 800 F, and has a maxima at intermediate frequencies. There are also indications that δ is increased by cold work and reduced by either steady or alternating magnetic fields. Its values should be obtained after prolonged vibration because of changes in damping capacity with number of cycles.

4.22 FATIGUE AND ENDURANCE

A metal may fail under sufficient cycles of repeated stress, even though the maximum applied stress is considerably less than the static strength of the material. This phenomenon is known as *fatigue failure*. Inspection of a great many of these fractures has shown that they invariably start with slip in individual grains. Repeated slipping of sufficient magnitude causes a minute crack to form. This crack (called *fatigue nucleus*) spreads across the grains with repetitions of loading until the remaining cross section of metal becomes too small to support the load, even in a static condition, at which time the part breaks.

The fracture is jagged, similar to a static break in cast iron or brittle steel. This appearance and the seemingly characteristic suddenness with which failure occurs gave some support to the former theory, first mentioned in 1849, that cold crystallization was the cause of failure. It has been shown, however, by many experts, that

this idea is incorrect. The sudden break displays the normal crystalline structure of the material, which in a static test is disguised to some extent by the distortion of the piece. The crystalline appearance is normally present only in the section which suffered the final break. The rest of the crack is usually smooth, owing to continuous rubbing of the sides of the crack during progressive fracture and possibly also to oxidation.

Tests of this type, which result in fracture, are usually called fatigue tests, whereas those which do not cause fracture are called en- | durance tests.

4.23   ENDURANCE TESTS

The endurance of materials is tested by submitting prepared specimens or entire product components to repeated cycles of applied loads and noting the number of cycles for fracture or for "life" without fracture. A number of samples are tested each under a different magnitude of the applied load. Results obtained are summarized by plotting the maximum stress on each specimen versus the number of stress cycles required to cause failure. Such a curve is called an *S-N* curve. On log-log coordinates it is usually a straight, sloping line down to some value at which it bends toward the horizontal, either gradually or sharply, depending upon the metal (see Fig. 4.23). Temperature, condition of material, the kind of stress, and its variation should be reported.

Fatigue Strength. Any point on the *S-N* curve to the left of the bend, or "knee," indicates a limiting stress called the *fatigue strength*, which will cause fracture in the corresponding number of stress cycles. On curve *F*, Fig. 4.23, for example, 15,000 lb per sq in. is the fatigue strength for 100,000 cycles of reversed bending of gray cast iron.

Endurance Limit. As the severity of the stress variation is reduced, the metal will withstand a larger number of stress cycles before fracture. The limiting stress below which the metal will withstand without fracture an indefinitely large number of cycles of stress is called the *endurance limit*. This stress corresponds to the asymptote of the *S-N* curve. The endurance limit can be established for most steels in about 10 million cycles which is beyond the break in the curve. But for the nonferrous metals, 500 million cycles is often necessary because their *S-N* curves do not show a pronounced knee. It may even be entirely absent, as is shown for Duralumin, curve *E*, Fig. 4.23.

A number of specimens have been standardized for the common testing machines. Most tests are made in reversed bending by canti-

lever loading or mid-loading of rotating beams. Cantilever flexure of strip under loads applied mechanically or pneumatically, and axial push-pull loads on bars are tests used less frequently. Specimens for any of these tests may be smooth and without stress raisers to determine the ultimate endurance of the material, or they may contain intentional notches or other stress raisers to determine, in
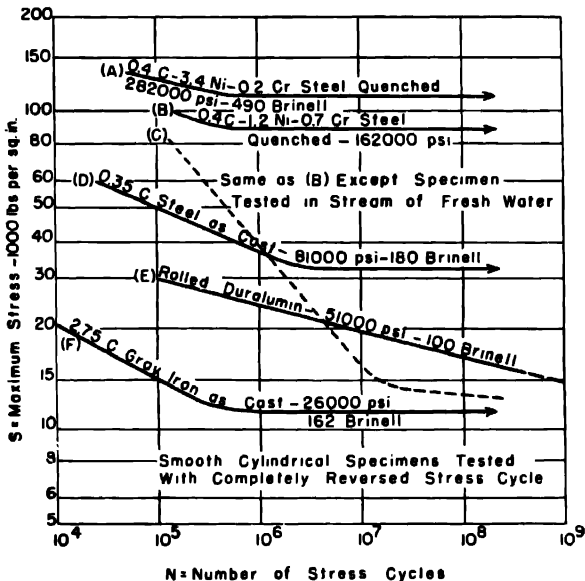
FIG. 4.23. *S–N* curves for some common metals. The values of stress on the curves are short-time tensile strengths. *Data from The Fatigue of Metals by H. F. Moore and J. B. Kommers.*

comparison with smooth specimens, the *notch sensitivity* of the material.

Notch sensitivity depends on the direction of the notch with respect to the load. Notches perpendicular to the stress are most severe. Notch sensitivity increases, in general, with hardness and cold working of both steels and nonferrous metals. There seems to be no direct correlation between notch sensitivity and ductility. Annealed copper is very notch sensitive, but brittle cast iron is not, nor is stainless steel, which has good ductility. Nor does notch sensitivity correlate with other mechanical properties, but the shape of the stress-strain diagram, the damping properties, the modulus of elasticity, and the work-hardening properties all seem to be involved.

Crack formation in the material is not always fatal, because under some conditions its propagation may be sufficiently limited so adequate life may be obtained from the part. The factors that determine the "period of grace" are the notch sensitivity of the material, the size of the part, i.e., the distance the crack must propagate, and the amount by which the stress exceeds the endurance limit. The life after initial damage may be particularly long if the stress which caused the damage was due to some heavy overload, quite large in comparison with the normal operating stress.

Because of the time and expense involved in making fatigue tests, numerous attempts have been made to correlate fatigue with other properties. No precise correlation has been obtained. Yield strength, tensile strength, and ductility seem to have some relationship. Perhaps the closest is the relation of endurance limit to tensile strength. The ratio between them is often reported as the *endurance ratio*. Values are about 33 per cent for many nonferrous metals. For steels the endurance ratio is usually 45 to 50 per cent, although values from 30 to 70 per cent have been obtained. It appears that for accurate results no short cuts can be used; fatigue tests must be employed. Whenever possible these should apply to the material, shape, and stress cycle to be employed in the design.

4.24 EFFECT OF STRESS CONCENTRATIONS ON ENDURANCE

The polished, smooth specimens used in laboratory endurance tests are seldom representative of parts in actual practice. "Stress raisers" are usually present in actual parts as re-entrant corners, holes, changes in sections, slag inclusions, residual heat treatment stresses, notches, tool marks, mill scale, scratches, welds, press fits, etc. Fatigue cracks will usually appear first at one or more of these stress raisers and will progressively increase in size until failure occurs. The *average* stress carried by the part may be well below the endurance limit. Nevertheless, if a stress above the endurance limit exists at some point in the part, progressive failure will start.

A good many of the stress raisers are surface effects and, in fatigue, start cracks on the surface. This suggests that fatigue nuclei can be detected by periodic inspection of parts in service, thereby permitting removal of faulty or damaged parts before actual failure occurs. The possibility of inspecting parts in service must necessarily be infrequent, however, in terms of the cycles of a load applied. In addition, cracks may be very difficult to detect, and fracture may occur very soon after the crack forms, thus allowing little time for detection

and replacement. For these reasons, preventive measures are by far the better cure. The first step is to handle the necessary stress raisers properly in the design, and then to insist on proper heat treatment, high-quality machine work, careful inspection before the part is accepted for service, and careful maintenance during its use.

The designer may take account of stress concentrations (other than those due to faulty workmanship) as follows: (1) Apply a correction factor to the endurance limits obtained with a smooth specimen of the material. Such strength-reduction factors for severe notches range from 3.85 for alloy steels to 2.85 for structural steels. Fillets and round notches have factors from 1.5 to 2.5 in steel and from 1.1 to 1.6 for cast iron. (2) Use as the design endurance limit a value obtained from test specimens similar to the part, or actual parts if time permits. (3) Design so the maximum concentrated stress is below the endurance limit of the material. This involves use of theoretical stress-concentration factors obtained from calculation or photoelastic studies. They result in overconservative design, however, because of the beneficial effects of plasticity in the regions of stress concentration. Since fatigue cracks advance without noticeable distortion, some degree of microscopic or submicroscopic yielding apparently mitigates the effect of such stress concentration.

The surface finish on a part acts as a stress raiser just as do notches and fillets. The reduction in endurance limit can also be as severe as for notches if the finish is rough. Values of endurance limit reduction for several finishes on a mild steel are given in Table 4.2 to illustrate

Table 4.2   Reduction in Reversed Bending Endurance Limit with Surface Finish for 0.33 Per Cent Carbon Mild Steel in Soft and Hard Condition

Surface Finish	Endurance Limit Reduction, %	
	Soft	Hard
Polished	0	0
Fine emery	2–3	6
Fine grind	4	8
Coarse emery	6	12
Fine file	7	14
Lathe turned	12	24
Accidental scratches	16	32
Rough file	20	40

the importance of surface finish in parts designed to support repeated stresses.

4.25   EFFECT OF STRESS CYCLE ON ENDURANCE

When endurance data for the actual stress cycle of a proposed design are not available, the permissible cyclic stress and superimposed steady stress may be estimated by diagrams such as those proposed by Johnson and Goodman, Launhardt and Weyrauch, Howell, Gerber, and others.

Goodman's Law. To define the region of fatigue failure for stress cycles imposed on mean loads between zero and the ultimate strength, Goodman proposed a straight line relationship which may be represented as shown in Fig. 4.24. This law can be stated mathematically by the equation

$$S_r = S_e \left(1 - \frac{S_m}{S_u} \right)$$

where S_r = one-half the total amplitude of the stress range, S_e = the endurance limit found by the reversed loading test, S_m = the mean value of the fluctuating stress, and S_u = the static ultimate strength of the metal for the same type of stress.

This equation gives endurance limits for the calculated combination of stresses. If only a limited number of cycles is expected, the fatigue strength for that number can be used in place of the endurance limit. Torsion, axial tension, and bending tests show that higher-than-calculated maximum stress can be supported at low values of mean stress, indicating that Goodman's law is conservative.

Yield-Strength Law. Parts designed to the limiting conditions of the Goodman law will be subject to some permanent deformation. Normally, this will occur on the first cycle of stress, and will not increase if the maximum stress is not raised. In designs such as a shaft supporting torsion, this deformation may be permitted without hindering the functioning of the part. In many parts, however, a small permanent deformation will cause interference or improper operation which is considered failure even though fracture does not ensue. The upper stress limit for designs of this type is the static stress which produces the damaging permanent deformation. As the mean stress approaches this yield strength (or yield point), the permissible cyclic stress must become smaller and smaller. The yield-strength law, illustrated also in Fig. 4.24, may be expressed by the equation

$$S_r = S_e \left(1 - \frac{S_m}{S_y} \right)$$

where S_y is the yield strength of the metal.

The dotted curve shown in Fig. 4.24 represents permissible maximum stresses determined by actual tests on a metal. Such a curve indicates the effect of work hardening, and although it varies for different materials, it shows the yield-strength law, too, to be conservative.
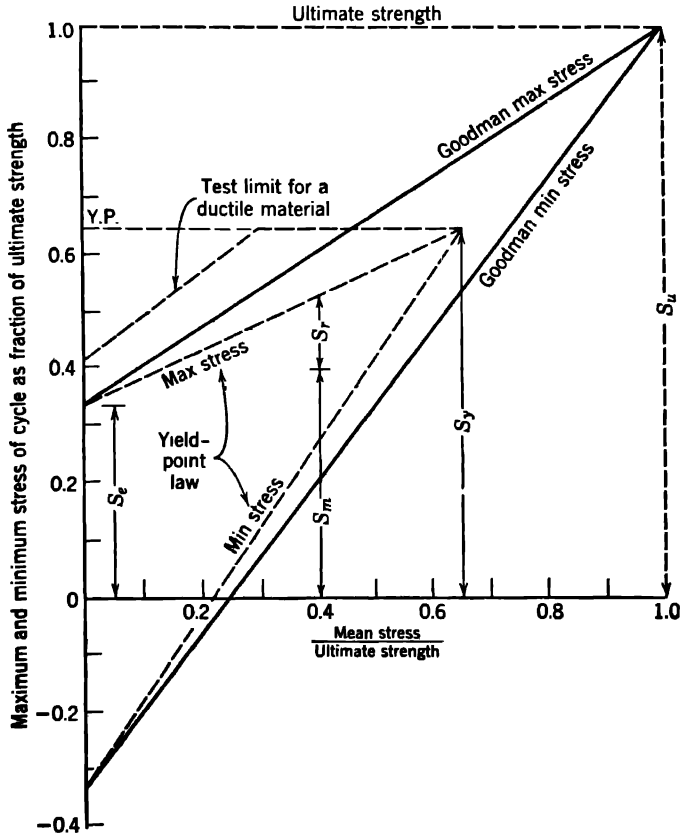
Fig. 4.24.   Effect of stress cycle on endurance.   Solid line is Goodman's law; dashed line is yield strength low; dotted line is maximum stress limit, with corresponding minimum stress from tests on one ductile steel.

Combined stresses caused by simultaneous action of mutually perpendicular tension, compression, or shear will change the locations of maximum stresses as in static load tests. The effect will sometimes be additive, sometimes reinforcing. The combined stress theories can be used as an aid in evaluating relation of combined stress fatigue to simple stress fatigue. Data on the actual combination are preferred when they can be obtained.

4.26 EFFECT OF OTHER VARIABLES ON ENDURANCE

The effects of other variables such as temperature, load frequency, surface treatment, corrosion, and load variation may, in particular cases, be as large as for stress concentrations or stress cycle. Some general observations on these effects are summarized below.

Temperature. Data available on steels at low temperatures indicate a higher endurance limit than for room temperature. Since higher tensile strength is also reported for the low temperatures, indications are that the endurance ratio remains nearly constant for subnormal temperatures.

Moderate elevation in temperature has only a minor effect on the endurance limit and may actually increase it by allowing plastic deformation when a metal might otherwise crack. A 0.14 per cent carbon steel, for example, showed a decrease of 9 per cent in static tensile strength at 750 F but had an increase of 16 per cent in 10-million-cycle fatigue strength at the same temperature.

For very high temperatures in the range of 1200 to 1500 F, the break is absent in the *S-N* curve for alloyed steels. Apparently they have no true endurance limit at these temperatures. Since fatigue strength values for 1000 hr for one alloyed steel were above the stress-rupture strength for the same time, design in this region sometimes must be based on rupture rather than fatigue.

Load Frequency. The energy lost in mechanical hysteresis may produce considerable heating when the speed of cyclic loading is high. If the endurance limit is affected by an increase in temperature, corresponding effects will occur with increased speeds. In steels no effect is noticed up to 5000 cpm, and a slight linear increase in endurance occurs at higher speeds. Where the magnitude of stress imposed depends on resonant vibration, the effect of both frequency and temperature on modulus of elasticity is an important consideration. It has already been mentioned that the E and G drop off with increase in temperature. Frequency affects the moduli at the very high temperatures through anelastic deformation, increased frequencies tending to raise the moduli values. Since few data are available regarding this effect, tests are needed for each application.

Surface Treating. Flame hardening and induction hardening increase the tensile-fatigue strength of steel bars and axles for repeated and pulsated loads, since residual compressive stress obtained in the surface by the hardening decreases the actual tensile stress produced by the loading. For other components, heat treating and hardening

may introduce internal tensile stresses at the same places where stress concentration will take place during fatigue. These effects are usually additive and severe stress raisers will result. Surface decarburization also usually decreases tensile fatigue strength by decreasing hardness and leaving a tensile stress in the surface.

Shot peening and cold rolling, particularly of fillets and other changes in section, also produce surface compression stresses. Increases of 15 to 25 per cent in reversed bend endurance limit have been obtained in this way, the smaller values applying to larger pieces.

Improved endurance may be obtained by cyaniding, carburizing, and nitriding. These operations change the surface material and this, in part, results in the improved resistance to fatigue. Nitriding also makes the material less notch sensitive, particularly for small notches.

Welded-on "reinforcements" may decrease the endurance of a part. Welds have practically every common type of stress raiser. The surface is rough, there are internal stresses caused by the localized heating, and slag inclusions and blowholes may be in the weld metal.

Size. The size of a part has a large influence on endurance values. At room temperatures, for example, a 1-in. diam bar of mild steel has 20 per cent less endurance limit than the same material tested in $\frac{1}{4}$-in. size. Large diameters up to 7 in. have even less endurance limit, although it is not certain whether this is due to size alone or to greater possibility of defects in material of such size. The larger sizes are also less influenced in reversed bending endurance by surface treating, probably because the surface shares a proportionately reduced share of the load.

Corrosion. Two effects of corrosion have been studied to some extent. One is corrosion on unstressed pieces prior to fatigue loading. The second is corrosion fatigue, that is, simultaneous corrosion and fatiguing. Both are effective in reducing the fatigue strength. The latter is particularly harmful and may cause reductions as high as 75 per cent. Cyclic stress accelerates pitting and pitting, as a stress raiser, accelerates failure. No endurance limit occurs; the stress that may be supported depends on the time the part is in use. Accelerated tests give incorrect values.

Load History. Understressing * definitely increases the total number of stress cycles that can be supported, and may raise the endurance limit as much as 25 per cent if the stress is gradually increased

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* Understressing means application of stress cycles at stresses below the endurance limit.

from at least 10 per cent below the virgin endurance limit. Periodic resting during the life of the part also seems to increase the endurance limit. Overstressing has the effect opposite to understressing, as it produces damage, causing early failure. There appears to be a limit of permissible overstressing before the "damage" occurs. Tests on steel show it to be a line from the break in the *S-N* curve intermediate between the fatigue strength line and the ordinate. Overstressing within this line does not lower endurance.

There is probably no single subject more important to mechanical engineers than fatigue. It is estimated that fatigue causes 90 per cent of the service failures of products. The many factors involved make the subject quite complex. Laboratory data must be applied carefully, making sure the data are representative of the conditions to be encountered in the actual part. Tests on actual components are probably most justifiable in fatigue problems, when they can be conducted.

4.27   WEAR RESISTANCE

Wear is a surface deterioration of contacting surfaces that destroys their operating relationship or causes rupture if carried far enough. The amount of wear depends on the nature of the contacting materials, the sliding, rolling, or impact motion between them, the load imposed, their lubrication, if any, and the chemical action of their lubrication and environment. Since these conditions introduce many types of wearing, no standard wear-resistance tests have been recognized. The tests performed in practice are designed to duplicate particular service conditions as nearly as possible.

In components which have metal-to-metal contact, wear may be the result of:

(*a*) Tearing of particles from the surface through friction.

(*b*) Production of cracks, pits, or fretting corrosion (false brinelling accompanied by red oxide in steel parts) through fatigue, high subsurface stresses, or stress, rubbing motion, and corrosion, respectively.

(*c*) Local removal of surface material, termed *galling*, with potentiality of actual seizure between the surfaces.

Metals which contact nonmetals wear by abrasion and erosion. Abrasive wear is generally reduced by choice of metal surfaces harder than the material to be handled.

Wear resistance of metals in contact is generally reduced by providing hard materials to reduce penetration of the surface, toughness

to prevent breaking off of small particles, and surface smoothness to eliminate projections. Similar materials may be used but, to reduce possibility of galling, dissimilar combinations or pieces of different indentation hardness are usually preferred. Solid-solution alloys should be avoided when loads are high enough to produce galling. Fine pearlitic steel is superior to ferritic steels in this respect. Choice of materials of high stiffness and materials that will form a protective tenacious corrosion product with the lubricant or the environment also aid galling resistance by preventing close atomic contact. Lubrication can reduce general wear if a thick film can be maintained. Boundary lubrication is of lesser value. When loads are light and lubrication is used, a shot-blasted or somewhat roughened surface shows less wear than a very smooth surface, because the roughened spots hold small reservoirs of lubricant, which maintain lubrication between the contacting surfaces. Cracks, pitting, and spalling generally indicate need for hard surfacing of materials or designing for lighter loads.

Among the old methods for designating abrasion or *scratch hardness* is the Mohs scale, which is based upon the relative hardness of the ten minerals: talc, gypsum, calcite, fluorite, apatite, orthoclase, quartz, topaz, corundum, and diamond, from the softest to the hardest. The hardness of other materials can be located on this scale by a scratch test, the harder material being capable of scratching the softer. For metals, particularly the steels, a file test is frequently used to cut softer metals in the shop to ascertain relative hardness. This method depends to some extent on the skill of the shopman to perform the test consistently. There are also other scratch testing methods employing metal or diamond points, and either measuring the scratch width for a given load (the Bierbaum microcharacter test for hardness of microconstituents) or the load for a standard scratch width.

4.28 CUTTING HARDNESS AND MACHINABILITY

Cutting hardness tests may be of two kinds: those applied to tools for determining their cutting properties, and those applied to materials that are to be machined. The latter determine resistance to cutting and are called "machinability tests."

It is current practice to determine machinability ratings of materials as power to cut the cold-drawn condition at 180 fpm in a lathe using normal cutting conditions and coolant with high-speed steel tools. A percentage figure is given for machinability in comparison

with values obtained on AISI B-1112 Bessemer steel screw stock. The ratings show variation between heats of the same material, and with different cuts, tool shape, tool material, cutting fluid, and different subject material treatment and surface conditions. Different processes such as milling, drilling, and broaching also affect relative ratings, because in some the material is torn, in others it is sheared or abraded. Such ratings are not absolute properties, but they are a useful guide in setting up factory operations prior to actual shop runs.

A misleading custom has grown up in the shops where difficulty with machining is often expressed by saying that the metal is "too hard to machine." Here, the word "hard" is used not in the technical sense of hardness, as measured by the Brinell machine, but as synonymous with "difficult." Frequently, a material classed as too hard to machine is really too soft to machine readily. This softness and toughness result in a tendency of the metal to tear and flow ahead of the tool rather than to be cut cleanly.

Impact Loads

4.29 IMPACT LOADS AND TESTS

Impact or shock loads differ from cyclic loads in two ways. First, the load is applied with appreciable velocity, usually sufficient to modify the characteristic response of the material; and second, the loading is seldom repetitive, failure occurring in the first application if occurring at all. Fatigue, as discussed in the last section, is not a factor in impact strengths, but cyclic loads that cause fatigue may also be of high velocity. Some designs which involve high-energy impact loads are steam hammers, punching and forming machines, landing gear on airplanes, gun mounts, internal-combustion engines, and numerous machinery and apparatus parts.

Impact testing is a comparatively new field of investigation, but it has been stimulated greatly by the necessity for finding materials to withstand the abuse of warfare. The first standardized tests were the Charpy and the Izod bending tests. More recently, high-velocity tensile tests have been developed, and explosives have even been used to cause very high velocity shocks.

4.30 BENDING IMPACT TESTS

In the Charpy and Izod machines a weighted pendulum is swung through an arc so as to fracture a carefully prepared specimen of the

metal.   The number of foot-pounds of energy required for fracture
(determined from the difference in potential energy in the pendulum
before and after the blow) is considered a measure of the *impact
strength*.   The only difference between the two tests is the shape of
the specimen and the type of support used.   The Charpy "Keyhole"
specimen is supported at both ends, and struck opposite a notch made
by drilling a through hole and relieving it on one side.   The Izod
specimen is of the end-loaded cantilever-beam type and contains a
"V" notch on the loaded side.   Both are sketched in Fig. 4.25.   There
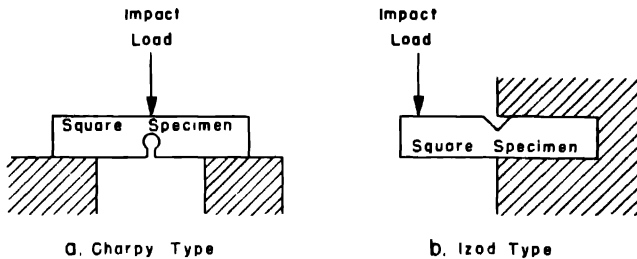
FIG 4 25.   Bending impact test specimens.

is also a Charpy "V" notch specimen.   All give quite different results,
hence the type used should be identified when quoting impact
strengths.

Since the notches act as stress raisers, the tests have some bearing
on notch sensitivity.   These tests also indicate, to a certain extent,
the ability of the material to support combined (three-dimensional)
stress, since the loading and shape cause a complex triaxial stress con-
dition.   The velocity of loading seems to have little effect in many
metals.   By comparison, changing the shape or the proportions of
the notch has a great effect.   Doubling the cross section, for example,
by eliminating the notch more than doubles the impact strength.   But
doubling the area by doubling the width of the specimen, and main-
taining the notch, has varying effects.   Actually, the energy required
for fracture may be decreased instead of doubled.

The bending impact tests are thus a qualitative indication of the
metal's sensitivity to notches and its ability to support combined
stresses.   But both single- and double-width specimens must be used
before the quality of the metal can be evaluated.   Sensitivity to
notches is apt to occur at low temperatures (in steel, anywhere from
+200 to −200 F), hence these tests are of great importance in locat-

ing the minimum working temperature for metals subject to shock loading.

4.31 TENSILE IMPACT TESTS

A machine for measuring the resistance of a material to high-velocity tensile impacts was developed in 1935 by H. C. Mann. In it a variable-speed flywheel delivers a tensile impact to a test bar similar to the bars used in ordinary tensile testing machines (see Fig. 4.26). The advantage of the test is that it permits study of the impact strength of a metal under a unidirectional stress and at various velocities. The effect of velocity on several steels is plotted in Fig. 4.27. Note that:

(*a*) For several metals, at velocities up to 30 or 40 ft per sec, there is a rapid rise in the energy required to fracture the metal and then a straight, slowly rising curve for greater velocities.

(*b*) Heat treatment ordinarily has an effect on impact resistance (see curves for brass).

(*c*) Malleable iron and normalized and drawn carbon steel have a peculiar dip in their curves; the curve for stainless steel shows it to require more energy for static rupture than for rupture at moderate impact velocities (25 ft per sec). An explanation for the shape of these curves has not yet been agreed upon, nor does it seem possible to predict the shape of the energy-velocity curve for a metal.

Curves of elongation versus velocity are shown in Fig. 4.28 for the same metals as illustrated in Fig. 4.27. In general, the elongation at fracture of the metal test bars increases gradually as velocity increases. Since a larger deformation allows a metal to absorb more energy before fracture, these ductility curves have a general upward trend the same as the energy curves, but no quantitative comparison is possible.

The shape of the tensile stress-strain curve is greatly affected by the rate at which stress is applied. Ordinary tensile tests are conducted at a strain rate of approximately 0.0003 in. per in. per sec and the curve is relatively smooth. If the stress is applied at a high velocity, however, tension and compression waves are set up which travel rapidly back and forth within the metal and cause the stress to oscillate as shown in Fig. 4.29. Only recently has the determination of these curves been successful, so their shapes have not been thoroughly explained.
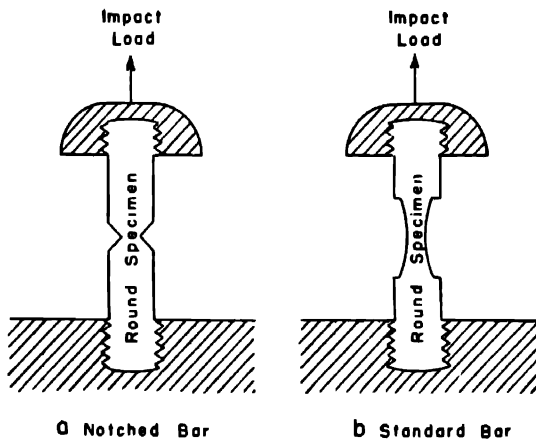
FIG. 4.26. Test specimens for Mann type of tensile impact.
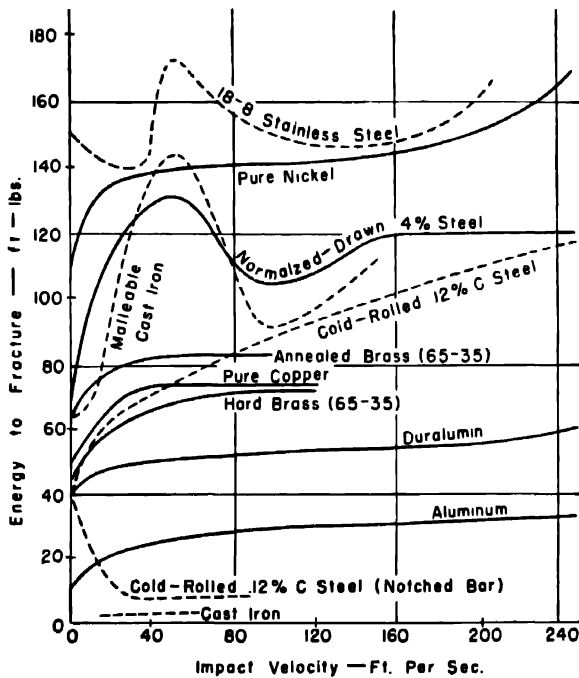
FIG. 4.27. Energy to fracture metals at various impact velocities. "Zero velocity" impact corresponds to the static tensile test.
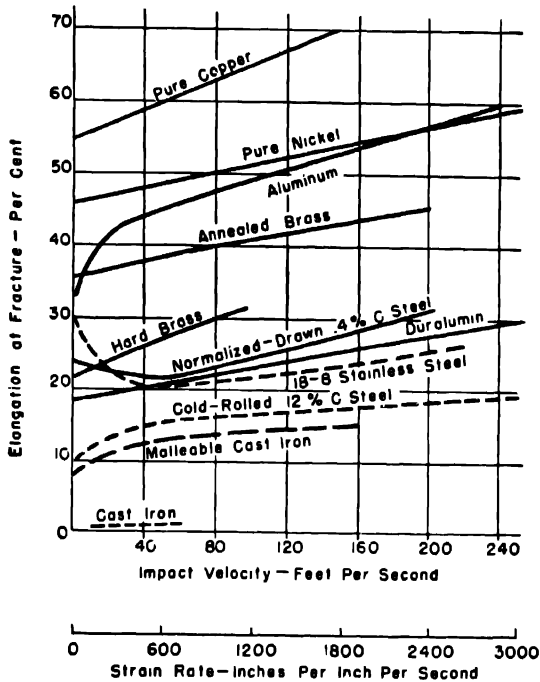
FIG. 4.28. Ductility of metals at various impact velocities.

Design

4.32 CRITERION OF FAILURE

Choice of material, proportions, treatments, and shape details for a particular part of a machine or structure obviously must provide for the desired service. For adequate service, the mechanical properties required in the material depend on the part form and loading: that is, on the manner or manners in which the part may fail. The criterion on which failure is judged is therefore an initial step in design of parts.

The general types of mechanical failure encountered in practice are:

(a) Permanent deformation under static load, which causes misalignment or binding of parts.

(b) Buckling collapse due to elastic instability.

(c) Creep at elevated temperatures, which causes interference of parts or relaxation of fits.
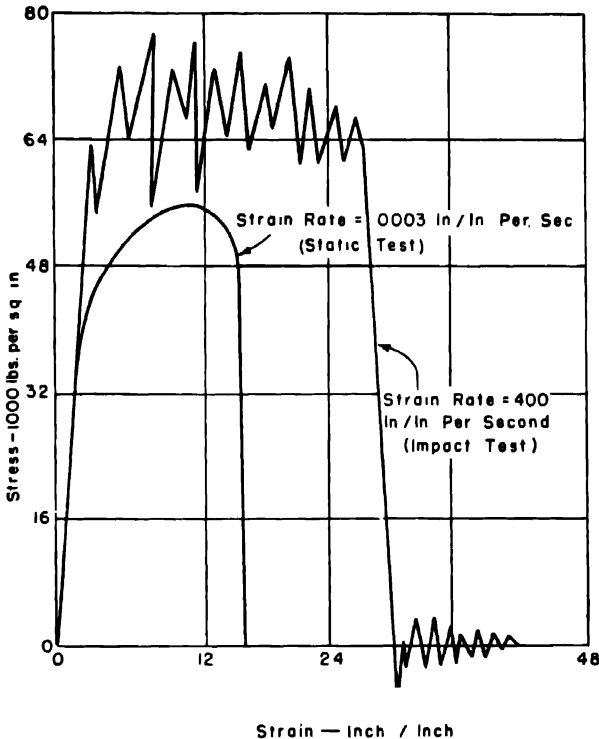
Fig. 4.29. Tensile stress-strain curves for Duralumin, loaded at two different speeds.

(d) Wearing away of parts, which destroys fits, or weakens sections until actual fracture ensues.

(e) Wearing that results in pits and cracks, which may cause parts to break.

(f) Wearing that results in galling and seizure of parts.

(g) Actual fracture resulting from insufficient strength for (1) static overload, (2) fatigue overstressing, (3) fatigue at unintentional stress raisers, (4) corrosion and stress, (5) impact overloads, or (6) impact cleavage fractures, usually at low temperatures.

It is significant that a part may fail to provide proper operation in several ways that do not involve actual breakage. This illustrates the need for determination of the criterion of failure for a design, and provision of the necessary properties in the material or rebalancing the part form and loading to survive the rigors of service.

4.33 THEORIES OF STRENGTH FAILURE

Considerable study has been given to the correlation of elastic theory with failure of materials. Particular interest has been placed on correlating strength failure under combined stress with simple tension tests. Five of the theories advanced are:

(a) Maximum normal (tensile) stress at any point under combined stress equal to the tensile stress at failure in simple tension constitutes failure (Rankin's theory).

(b) Maximum strain at any point under combined stress equal to the strain at failure in simple tension constitutes failure (St. Venant's theory).

(c) Maximum shearing stress at any point under combined stress equal to shearing stress at failure in simple tension constitutes failure (Guest's theory).

(d) Maximum strain energy at any point under combined stress equal to this energy at failure in simple tension test constitutes failure (Beltrami and Haigh).

(e) Maximum distortion energy at any point under combined stress equal to this energy at failure in simple tension test constitutes failure (Hencky, Von Mises, and others).

The maximum-stress theory (Rankin) appears to have close agreement with experiment for brittle materials. For both brittle and ductile materials, the maximum-shearing-stress theory appears somewhat conservative but is often used because of its simplicity over strain-energy and distortion-energy theories. The latter is probably in closest agreement with available data for ductile materials. Use of the maximum-shearing-stress theory is aided by determining the maximum shear stress on oblique planes by use of Mohr's circle or similar analysis.

Some work has been done to apply these and other theories to plastic flow and fatigue. For discussion of these topics see the works of Nádai and Marin listed at the end of the chapter.

4.34 STRESS DETERMINATIONS

The stresses present in a part can be calculated mathematically, using elastic theory when the shapes are not complicated and when the magnitudes of the applied loads are known. Often, however, the part shape is complicated and does not lend itself to accurate analysis. For such parts the stresses may be determined by one of several experimental methods. Sometimes photoelastic testing may be em-

ployed by studying a suitable transparent plastic model under polarized light. This method is particularly helpful for parts containing stress raisers, although in ductile materials some yielding may take place to reduce the stress concentration, thus permitting a larger load to be supported. Dynamic loads and the maximum stresses they produce may be measured in simulated tests on models or in actual service tests on parts through use of stress coatings (brittle lacquers) or strain gages. The stress-coat method involves coating the part prior to loading. The lacquer obtains a controlled brittleness in curing. Under test it will crack when local tensile yielding reaches a limiting value, thus indicating regions of high stress and strain. Relaxation methods can be used for detecting high compressive stress. In either application, careful control of the lacquers is essential to good results. The strain-gage method, using either carbon gages or nichrome wire gages whose resistance changes with local strain (inductive and capacitance gages are also available), provides a more accurate measure of strain. But the points of highest stress must be anticipated, since equipment and space limits the number of gages that can be applied.

Residual Stresses. Analysis of residual stresses in fabricated parts is often important, since such stresses may be additive with applied load stresses and may decrease the strength of the part. Four general methods have been used for this purpose.

The most widely used method is based on the elastic strain that will result upon release of the "locked-up" load by removal of some of the material. One procedure, proposed by G. Sachs, involves drilling out cylinders or tubes in several steps and measuring diameters and lengths. Original residual stresses are then calculated from the relaxations. Strain gages or other accurate strain-measuring equipment is required. Residual stresses in tubes may also be determined by change in curvature resulting from parting with acid or an abrasive wheel. The stresses in plates may be determined by curvature change upon machining from the surface.

A second method involves use of brittle lacquers which are coated and cured on the surface. A hole is then drilled through the lacquer. Star-shaped relaxation patterns indicate residual tension at the point drilled; concentric circles indicate compression. Magnitude of the stress is determined through repeated trials with calibrated coatings

A third method is to detect by X-ray diffraction the difference in atom spacing in the material as a result of stress. This method is

still in the developmental stage and requires expensive equipment, but it appears promising, especially for surface stresses.

Another method that appears to have promise is correlation of internal stress with total core losses under a high-frequency magnetic field. Investigations by P. E. Cavanagh * indicate that correlation is possible and, although there are a number of practical difficulties, successful production applications have been made.

4.35 FACTOR OF SAFETY

Consideration of the criterion of failure, the theories of strength failure when this is involved, and determination of loading and residual stress lead to determination of a *damaging stress* for the material. This stress is the minimum stress which, if exceeded in the material, would render the part unfit for service before the end of its normal expected life.

The actual stress that the part will be designed to handle is termed its *working stress.* This stress would be chosen ideally as just slightly below the damaging stress, and maximum strength utility of the material would then be realized. In practice, however, working stresses are designed to be much lower than the damaging stress.

The ratio of damaging stress to working stress is called the *factor of safety.* If the designer were to know with exactness the properties of the material, the nature and magnitude of the expected load, and the way the load would distribute itself within the material, he could design using a factor of safety of unity. Actually, he uses factors of safety from 1.2 up to 20. Some of the conditions that affect the choice of a factor of safety are:

(*a*) Variations in the properties of the material because of structural heterogeneity, possible presence of inclusions and blowholes, and size effect.

(*b*) Inaccuracies in determining the magnitude and distribution of load stresses. Also under this classification are the errors introduced by the assumptions underlying the theory used, and the assumptions made to reduce the actual problem to one that could be handled by mathematical theory.

(*c*) Residual heat-treatment and cold-working stresses, stresses caused by assembly or thermal gradients, or stresses due to handling.

(*d*) Variations in time effects, such as uncertainties in creep, brittleness, corrosion, fatigue.

* Paper presented at 1945 A.S.M. annual meeting, entitled "Stress Comparisons by Correlation with High Frequency Magnetic and Eddy Current Losses."

(e) Importance of economy of weight or material.

(f) Risk of life or financial loss that is involved. Sometimes members are provided to assume the load in case of failure of the main load carrier; for example, the double fork for motorcycles.

(g) Quality of workmanship (fits, tolerances, absence of tool marks, etc.).

Some factors of safety in common use are as follows:

(1) For static loading of steels and other ductile metals, if the elastic limit is the damaging stress, the factor of safety (N) is usually chosen as 2. Higher values are required for pressure vessels. If stress raisers are present that may relieve themselves by ductile flow of the metal, or if the severest overload instead of the normal load has been used in computing damaging stress, N may be less than 2—the working stress being the maximum stress at the stress raiser, or caused by the overload.

(2) In airplane design, a, b, and g above are carefully controlled and determined, and, consequently, good results are obtained from the use of N's below 1.5.

(3) For static loading of cast iron, the ultimate strength is usually the damaging stress, and factors from 4 to 10 are chosen.

(4) Under fatiguing conditions, fatigue strength or endurance limit is the damaging stress, and N is about 2.5 or 3 where conditions are good, 3 or 4 in the presence of stress raisers, and even more if corrosion may take place.

It may be seen that the factor of safety has a wide range of values and its choice depends ultimately upon the experience and good judgment of the designer. A designer should not attempt to use factors too radically different from those which have been proved by experience, unless a very careful study of the variables indicates that reductions are feasible.

4.36 CONCLUSION

The subject of mechanical properties of metals is very broad and diversified and it has therefore been necessary to limit this chapter to only a brief discussion of the salient points. Over a period of years, the work of many colleges, suppliers, and industrial research groups has made available vast quantities of data. It is recommended to the designer who makes use of these data that they be employed with care. Lack of thorough evaluation of the meaning of the test properties with respect to the operation of the material in service can easily result in faulty application.

The designer is also urged to keep abreast of the developments. New developments seem particularly rapid and significant in this field and may make possible tomorrow something that is impossible today, because a material having the necessary properties is not now available.

Review Questions

1. Explain the difference between the following: (a) Elastic limit and proportional limit. (b) Yield point and yield strength. (c) Toughness and resilience. (d) Endurance limit and fatigue strength.

2. A carbon-steel motor shaft has been found to deflect too much in service. It has been suggested that an alloy-steel shaft of the same size but having a higher elastic limit would remedy the trouble. Point out the fallacy.

3. Discuss strength and stiffness of materials as related to component parts.

4. Name three factors which may cause differences in properties from those usually reported in the literature.

5. Why is ductility considered important in materials? Name four tests for evaluating formability of materials.

6. What is the approximate Brinell hardness number of a mild steel whose static tensile strength is 70,000 psi?

7. What is meant by transition temperature, and what materials are subject to this characteristic?

8. How do mechanical properties behave with increased temperature?

9. (a) What two structural changes in the material tend to balance each other during the second stage of creep? (b) What is the difference between creep rate and total creep?

10. Why is damping capacity important in metals for parts subject to vibration near their resonant frequency?

11. Describe how metals fail in fatigue.

12. Name six types of stress raisers that may increase susceptibility of a part to fatigue failure.

13. What are the effects of load cycle, temperature, frequency of loading, surface treatments, size, corrosion, and load history on fatigue of a part?

14. How do metals fail by wearing? Name several factors involved in choosing compatible materials.

15. What information does the design engineer obtain from impact tests?

16. Name five criteria of mechanical failure of parts.

17. How may residual stresses resulting from processing or proof test be determined?

18. Define the factor of safety and give six factors that affect its value.

5 CORROSION AND TARNISHING PROPERTIES

OF METALS

5.1 INTRODUCTION

Each year corrosion and tarnishing cause millions of dollars worth of damage in the United States to structural and decorative metal parts. Annual replacements or maintenance have been estimated to average as much as 2 per cent of the total tonnage of metal in use. An appreciation of these phenomena and methods of limiting their effects are therefore essential to engineering, both because of the tremendous economic waste involved and because of the possible risk to human life.

Corrosion may be defined as the destructive chemical or electrochemical reaction of a material and its environment. Corrosive action is usually associated only with metals in contact with liquids. It is considered separate from destruction by mechanical means, such as erosion and abrasion, although corrosion and mechanical action often operate together, promoting each other. Corrosion of metals may serve either to disfigure products or to reduce their strength so that rupture ensues.

Tarnishing is defined as a chemical reaction of a metal with its environment. It results in formation of films which coat the metal. When the films are chemical compounds having color, the tarnish may serve to disfigure the product. When the films are periodically removed, the attack will be continually renewed, with possibility of metal removal sufficient to impair the strength.

Discussion of corrosion and tarnishing are separated to facilitate presentation. Principles of corrosion and corrosive behavior of common metals are covered first. Tarnishing fundamentals and metal behavior follow.

Principles of Corrosion

5.2 CORROSIVE ATTACK

Contact between a metal and a liquid solution results in corrosive attack. In many instances the attack may proceed so slowly that it is scarcely noticeable. In others it may proceed initially at a fast rate, then arrest itself before serious damage ensues. The most serious possibility is that it shall proceed unabated and result in product failure. The degree of attack depends on the metal and the environment, but no metal in use today can avoid corrosive attack in all environments. All will corrode under certain conditions.

Corrosive attack is considered *direct* if the immediate products of the corrosion are deposited on the metal. When these corrosion products are insoluble in the solution, their deposit provides a protective insulating film. The rate of attack then diminishes, being inversely proportional to the film thickness. But if the immediate corrosion product is soluble in the solution present, it will dissolve after its formation, thus leaving the metal exposed for continuation of the attack.

Two-stage attack occurs when the immediate corrosion product further reacts with the solution to form a second corrosion product. These second-stage products are usually less soluble than the immediate product of the corrosion. Their value in stifling the corrosion again depends on the location at which they precipitate. If they are deposited in tenacious physical contact with the metal, they will be protective. If deposited at small distances from the metal surface, but out of physical contact, they are nonprotective.

The term *electrochemical attack* is usually applied to those corrosion reactions in which electric currents flow for perceptible distances in the metal. This condition occurs when immediate or second-stage corrosion products are deposited at some distance from the area undergoing corrosive attack. It also results from contact between dissimilar materials and from differences in solution concentration or metal concentration at nearly adjacent locations.

These three types of attack form the mechanisms commonly encountered in corrosion reactions.

5.3 THE ELECTROCHEMICAL THEORY

Most chemical reactions may be considered electrochemical in the sense that they are accompanied by transfer or displacement of electrons. The theory that relates chemical action to the electron flow

prevailing is known as the electrochemical theory. Although it cannot be said that this theory will explain all types of corrosion, it does cover the common reactions about which most is known. It will be used as the basis for further discussion.

According to the electrochemical theory, the region surrounding a metal which is being corroded must fulfill three conditions. (1) At least two areas on the metal surface must act as electrodes for the flow of electrons (electric current) from the metal into the solution and back again. (2) The solution and the metal must be capable of conducting some electrons. (3) A driving force or electric potential must set up the current flow. This potential is usually set up through *ionization*.

5.4   IONIZATION

When a metallic atom dissolves in a solution, it gives up one or more of its electrons and the charge remaining is positive. This residual part of the atom carrying a positive charge is called an *ion*. The solution in which the ions exist is called an *electrolyte*.

When a metal capable of existing in a solution as ions is placed in water or some other dissolving agent, part of the metal will pass into this solution as ions carrying a positive charge. The remaining metal will be charged with an equivalent negative potential. The potential difference established between the metal and the solution is termed the *solution potential* or *solution pressure*. It is the driving force which determines the metal's initial tendency to corrode.

The solution pressure of a metal has a characteristic value at a specified concentration of its ions in the solution. A different concentration results in a different potential. Potentials measured at a concentration of 1 mole per 1000 g of water between various metals and hydrogen are listed in Table 5.1. This table is known as the *electromotive-force series*. The terms *electromotive series* and *electrode-potential series* are also used. Lower hydrogen-ion concentration tends to move hydrogen up in this series relative to the metals. An increase in metal-ion concentration tends to move the metals down relative to hydrogen. The negative-electrode metals form positive ions and leave the remaining metal negatively charged. These metals tend to displace hydrogen from the solution. The positive-electrode metals also tend to dissolve, but more feebly.

Water, H_2O, dissociates into positive hydrogen ions (H^+) and negative hydroxyl ions (OH^-). A water solution (the electrolyte) will thus contain H and OH ions as well as ions from any dissolved

Table 5.1*   Electromotive Force Series

Element	Symbol	Standard Electrode Potential, in volts at 25 C
Potassium	K	−2.922
Calcium	Ca	−2.77
Magnesium	Mg	−2.34
Beryllium	Be	−1.70
Aluminum	Al	−1.67
Manganese	Mn	−1.05
Zinc	Zn	−0.762
Chromium	Cr	−0.71
Iron	Fe	−0.440
Cadmium	Cd	−0.402
Cobalt	Co	−0.277
Nickel	Ni	−0.250
Tin	Sn	−0.136
Lead	Pb	−0.126
Hydrogen	H_2	0
Antimony †	Sb	+0.1
Bismuth †	Bi	+0.226
Copper	Cu^{++}	+0.345
Copper	Cu^+	+0.522
Mercury	Hg_2^{++}	+0.799
Silver	Ag	+0.800
Palladium	Pd	+0.83
Mercury	Hg^{++}	+0.854
Platinum	Pt	+1.2
Gold	Au^{+++}	+1.42
Gold	Au^+	+1.68

Anodic. Electrode Negative to Hydrogen

Cathodic. Electrode Positive to Hydrogen

* Uhlig, H. H., *Corrosion Handbook*, 1st edition, John Wiley & Sons, New York, 1948.
    † International Critical Tables, Vol. 6, McGraw-Hill Book Co., New York, 1929.

acids, alkalies, and salts. Acids dissociate into positive hydrogen ions and negative ions of the nonmetallic radical.

Hydrochloric acid $HCl \rightleftharpoons H^+ + Cl^-$

Sulfuric acid $H_2SO_4 \rightleftharpoons 2H^+ + SO_4^{--}$
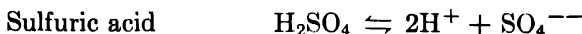
Alkaline solutions dissociate into hydroxyl ions and positive ions of a metal or metal-like radical.

Caustic soda $NaOH \rightleftharpoons Na^+ + OH^-$

Ammonia water $NH_4OH \rightleftharpoons NH_4^+ + OH^-$

Salts dissociate into positive ions of a metal or metal-like radical and negative ions of a nonmetallic element or radical.

Table salt $NaCl \rightleftharpoons Na^+ + Cl^-$

5.5   SINGLE-METAL CORROSION

Before a metal contacts a water solution, the solution will be electrochemically neutral. That is, the total charge of positive ions will be equivalent to the total charge of negative ions. The contact with metal introduces metallic ions which upset this neutrality. To restore equilibrium (the natural tendency of chemical action) either ions of negative potential must be added from another source, or positive ions must be displaced from the solution. In single-metal corrosion cells the latter action takes place because there is no other ion source. The displaced ions may be those of another metal (from the salt), or, more frequently, those of hydrogen. A metal above hydrogen in the electromotive-force series tends to combine with the negative radical, consequently displacing hydrogen in the solution. For example,

$$Fe^{++} + 2H^+ + 2(OH)^- \rightarrow Fe(OH)_2 + 2H^+$$
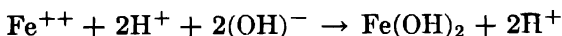
The higher the metal in the electromotive force series, the greater its tendency to displace hydrogen. The displaced hydrogen ions will migrate to the metal, take up the residual negative charge, and reestablish equilibrium [$H^+ + (electron)^- \rightleftharpoons H$, atomic hydrogen]. The area that receives the hydrogen is called the *cathode;* for single metals in an electrolyte, it may be adjacent to the *anode*, the area at which the metal is dissolving. The "plating" of a film of hydrogen

on the cathode, however, obstructs the reaction (*a*) by insulating the metal from the solution, and (*b*) by the tendency of the atomic hydrogen in the film to re-enter the solution, thus opposing the tendency for the metal to dissolve.

If the corrosion is to proceed, the atomic hydrogen film, or "plate," must be removed. This removal, or *depolarization,* can proceed by either of two methods: (1) changing the atomic hydrogen into the molecular form which escapes as bubbles of gas, or (2) combining the hydrogen with free oxygen in the solution to form water.

The voltage required to cause atomic hydrogen to combine into molecules depends upon the ion concentration in the electrolyte. Table 5 2 lists such data, but they apply only to a standard black-

Table 5.2   Ion Concentration

Potential of Hydrogen * on Saturated Platinum Plate	pH	Concentration, g moles per liter	
0	0	1	
−0.058	1	0.1	
−0.116	2	0.01	H$^+$ ions or acid so-
−0.174	3	0.001	lution
−0.232	4	0.0001	
−0.290	5	0.00001	
−0.348	6	0.000001 ⌡	
−0.406	7	0.0000001	H$^+$ and OH$^-$ ions or neutral solution
−0.464	8	0.000001	
−0.522	9	0.00001	
−0.580	10	0.0001	OH$^-$ ions or alka-
−0.638	11	0.001	line solution
−0.696	12	0.01	
−0.754	13	0.1	
−0.812	14	1	

* Voltage required to form molecular hydrogen on a blackened platinum plate. For most other metals the voltage required is greater, and the difference between the voltage required for other metals and that given above is the *hydrogen overvoltage* of the metal.

ened platinum electrode. Most other electrodes require an even greater negative voltage, and the difference between the voltage required for blackened platinum and that for another material is the *hydrogen overvoltage* of that material.

Table 5.3 is a list of metals in decreasing order of their hydrogen overvoltage. Zinc, at the top of the list, will resist corrosion even

by moderately strong acids if oxygen is excluded, because of the difficulty with which hydrogen gas (molecular) forms on the surface.

Table 5.3*

Overvoltage Series

Zinc
Mercury
Magnesium
Cadmium
Aluminum
Tin
Lead
Chromium
Gold
Copper
Silver
Iron
Cobalt
Nickel
Platinum
Carbon

5.6   TWO-METAL CELLS

The simplest form of the two-metal cell (also known as *galvanic cell*, or *galvanic couple*) consists of two metals connected with each other and immersed in a single solution (see Fig. 5.1). The individual solution pressures cause each metal to dissolve in the solution, and hydrogen is plated on both metals. When oxygen keeps both surfaces depolarized and only one metal is corroded, the amount of corrosion is approximately the same as would result from corrosion of a single metal having the same total surface area. Fig. 5.2 shows the corrosion of a bar of clean steel and a bar made up from half-length bars of steel and copper in thoroughly aerated tap water. After a few days, the weight loss per unit of time becomes essentially the same for the steel bar as for the steel-copper bar. The depth of penetration in the steel of the steel-copper cell would be greater than for the steel bar alone because the same amount of metal is corroded
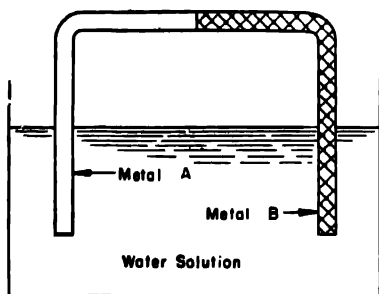

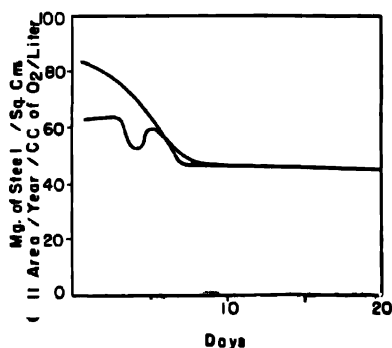Fig. 5.1. Simple two-metal galvanic corrosion cell.

Fig. 5.2. Corrosion of clean steel bar, lower curve, and steel-copper bar of same size, upper curve, in thoroughly aerated tap water.

* The position of the metals in this series varies to some extent with the electrolyte used in making the tests and with the electrode current density.

from a smaller area. In other words, *the smaller the anode com-pared with the effective cathode, the greater the penetration.*

The rate of corrosion increases with the separation of the metals in the electromotive series. The higher potential, other conditions being constant, causes a larger electron flow and more corrosion.

The corrosion rate at the anode will be greater if molecular hydrogen can form on the cathode metal. Low hydrogen overvoltage is conducive to the formation of molecular hydrogen, so contact between iron and carbon (lowest in the H overvoltage series), as occurs in gray and malleable cast irons and in graphited steam packings, gaskets, etc., will increase the rate of corrosion of the iron. The galvanic cells set up between a metal and slag inclusions or scale, corrosion products, etc., on the surface may act in the same way. This is the reason some metals show better corrosion resistance when they are of great purity and when their surface is clean and smooth.

5.7 CONCENTRATION CELLS

The potential or driving force in concentration cells may be caused by differences in the solution in contact with adjoining areas of one metal surface. The solutions may be of different substances, or merely two solutions of a single substance which vary in acidity, alkalinity, or oxygen concentration. Such cells can set up potentials of the same order of magnitude as those of the two-metal cells.

When solutions of two different substances set up the cell, the anode solution is the one which dissolves the metal. The cathode solution releases the positive ions which are "plated" on the cathode region. When concentration cells are formed by two solutions of the same substance, the metal in contact with the more dilute solution is anodic.

The precipitation of layers of insoluble corrosion products which are not continuous or impervious may also set up such cells by preventing free contact with fresh solutions at the anode area. Once started, these cells tend to be self-perpetuating, because the poor contact at the anode gets poorer, thus providing a greater electrical potential.

A simple oxygen concentration cell is set up within a drop of water such as might condense on an iron or steel plate. As the oxygen in

the drop is used, more oxygen enters from the free surface of the drop. But the distribution of oxygen becomes uneven, the concentration being greatest at the outer edge. A cathode is thus established near the boundary of the water drop, and surrounding the anode (where corrosion occurs) at the center of the drop.

The nature of the action going on in the drop can be demonstrated by using a drop of ferroxyl indicator (a mixture of water solutions of phenolphthalein, potassium ferricyanide, and sodium chloride).
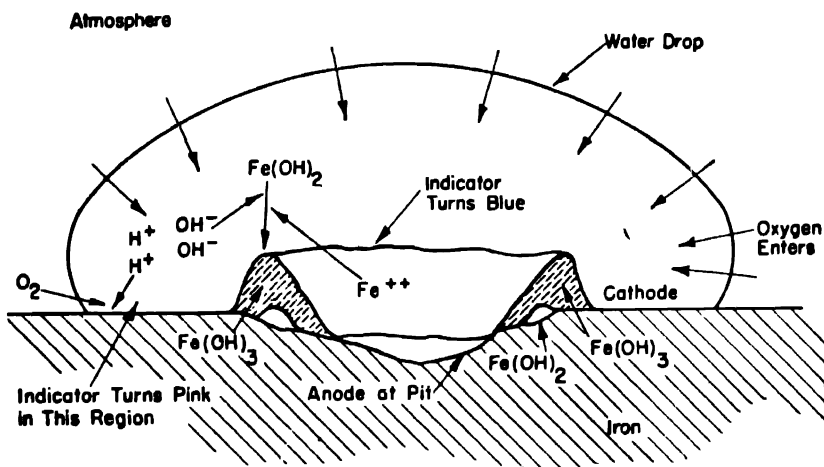
FIG. 5.3. Oxygen-concentration cell set up by a drop of water on a piece of iron. The action involved is indicated by a ferroxyl indicator.

The phenolphthalein in the indicator turns pink in the presence of excess hydroxyl (OH^-) ions, and the potassium ferricyanide turns blue in the presence of excess ferrous ions (Fe^{++}). A trace of salt (sodium chloride) is added to make the corrosion proceed rapidly enough for a good demonstration.

When a drop of the solution is placed on the iron surface, the oxygen concentration at the center of the drop is quickly reduced and a concentration cell is set up. The center of the drop (anode) turns blue, and the edge of the drop (cathode) turns pink. The colors will be best defined if a polished metal specimen is used. The ferrous hydroxide, $Fe(OH)_2$, in time forms in the solution, then is oxidized to the brown ferric hydroxide, $Fe(OH)_3$, and precipitated around the anode as common rust, Fig. 5.3. The deposit of corrosion products around the anode acts to exclude oxygen even more completely from

the center of the drop and thus increases the electrical potential of the cell. If the cell operates for a long enough time, a pit will be formed at the center of the drop.

In addition, the deposit of ferric hydroxide excludes oxygen from the metal beneath it and forms another oxygen-concentration cell. Since the rust which has been deposited acts as a permeable membrane to the electrolyte, permitting some flow of ions, a small amount of green ferrous hydroxide, $Fe(OH)_2$, forms under the heap of rust.

An interesting example of concentration cell corrosion occurs on iron or steel parts such as posts that are in contact with water and air simultaneously. When the water is steady, pitting results just below the waterline. The usual explanation is that the extra concentration of oxygen at the free surface causes that area to be cathodic with respect to an area under the surface, and the resulting concentration cell then causes corrosion at the latter area. The action is no doubt influenced and accelerated by semiprotective corrosion deposits which form near the surface and slide down over the anodic areas, further limiting the oxygen concentration. If the level of water is constantly changing, as with waves and tides, the corrosion will be greatly accelerated over the entire wetted surface, mostly because of the direct exposure to oxygen.

5.8 CORROSION RATES

In single-metal corrosion with solutions that result in either direct attack or two-stage attack, the entire surface of the metal will be uniformly corroded. The rate of corrosion in weight removed per unit time gives a true picture of corrosion for such cases. Suitable allowances in thickness may be made to assure the required life.

Two-metal cells and concentration cells, by comparison, tend to confine the corrosion to a localized region. Although the metal removed may be only a small amount, localization of the corrosion may cause deep pits, which can seriously reduce strength and even cause perforation. The rate of corrosion in these cases must be considered in relation to the factors which promote localization.

5.9 INFLUENCE OF THE METAL

There are four main characteristics attributable to the metal that influence corrosion rates. Two of them, electrode potential and hydrogen overvoltage, have already been discussed. The other two are (1) chemical and physical homogencity of the surface, and (2) ability to form protective films.

Homogeneity of the Surface. Lack of homogeneity, either chemical or physical, in the metal surface promotes the formation of galvanic cells. Chemical examples include metals containing two or more alloy phases, segregation, lamination, or impurities. Designs involving two different metals in close contact or metals with discontinuous coatings are also of this type. An important example of corrosion of two-alloy phases is *dezincification*, which derives its name from the electrochemical removal of zinc from brasses. The action is a combination of a galvanic cell, which removes the zinc and plates the copper at a cathode, and a concentration cell, which replates the copper back on the original anode in spongy, weak "plugs." The phenomenon has also been encountered in aluminum bronzes, cast irons (iron and graphite), and other alloys containing elements with widely different electrochemical potentials.

Physical examples of nonhomogeneity include differences in surface roughness and presence of mill scale, dirt, etc. The mechanism of pit formation on a large steel surface in contact with water, e g , a boiler or tube surface, depends upon a break in the surface scale, a deposit of foreign particles, or some similar means to start an anode. After the cell is established, it may form a permeable membrane of corrosion products over the pit, and the material beneath the pit will be the green ferrous hydroxide, $Fe(OH)_2$. If oxygen is not present, as in a closed hot-water heating system, only the ferrous hydroxide, $Fe(OH)_2$, can form, and that only to a limited degree.

Nonuniform surface stresses produced by heat treatment, cold working, or applied loads are also of this type. The corrosion that results is called *stress-corrosion cracking*, or, in brass, *season cracking*, after the seasoning cracks that develop in wood. Cracks are produced locally in regions of high stress, usually near the yield point, and they grow mainly along the grain boundaries. The condition is not limited to one material or to one corrosive medium. Low-carbon steel is affected by caustic solutions, stainless steel by acid chlorides, high zinc-bearing aluminum or magnesium and aluminum-magnesium al-

loys by sea water, and copper alloys, especially high-zinc brasses, by mild ammonia. Reduced stresses, through reduced external loads and application of stress-relief treatments, and protection of the metal are the means used to avoid corrosion cracking.

Ability to Form a Protective Film. This characteristic has been of great importance in industrial applications. Unfortunately, films are formed on only a few metal-alloy groups such as aluminum, chromium, silicon, and chromium-bearing "stainless" steel. Soon after the corrosion of these metals has started, such an impervious film is formed that corrosion may be stopped completely. Fig. 5.4 illustrates how the rate of corrosion of two chromium-bearing steels is reduced with the formation of the protective film. If it is desirable to form this protective film before

Fig. 5 4. Corrosion of two chromium-bearing steels compared to low-carbon steel Note reduction of corrosion rate of the Cr steels with formation of a protective film.

the part is actually put into service, a controllable corrosion treatment, called "passivation," is used. Since most of the protective films are oxides, the passivation treatment usually requires an oxidizing solution.

5.10 INFLUENCE OF THE ENVIRONMENT

It is difficult to evaluate completely the effect of the many environmental conditions on the corrosion rate of a metal. Factors governing corrosion in one case may be negligible in another. For this reason, each corrosion problem must be handled individually. The factors that are most often of importance are the electrolyte, the tendency for depolarization to occur, the effect of corrosion products, and the duration of exposure. Each of these factors is discussed in the following paragraphs.

5.11 INFLUENCE OF THE ELECTROLYTE

Electrochemical corrosion has been shown to depend on the displacement of hydrogen ions from solution. Since the deposition of ions is favored by high concentrations, it follows that the corrosion

rate is increased with hydrogen-ion concentration, all other things being equal.

One characteristic of aqueous solutions is that the product of the H- and OH-ion active concentrations is a constant, which, at room temperature, is approximately 10^{-14} gram mole * per liter of solution. As pure water is electrochemically neutral, it must have an equal number of H and OH ions, or 10^{-7} gram mole per liter of each. Acids dissociate into H ions, and so acid solutions must have more than 10^{-7} mole per liter of H ions. Alkaline solutions would likewise have more than 10^{-7} mole per liter of OH ions. The H-ion concentration is expressed as

$$pH = \log_{10} \frac{1}{\text{H-ion concentration (gram moles per liter at 71.6 F)}}$$

For the relationship between pH and H ions, see Table 5.2.

ACIDS   The acids may be divided into three classes according to their action in corrosion processes.

(a) *Strong, nonoxidizing acids,* such as hydrochloric and sulfuric, depend upon an external oxygen supply for depolarization. Concentrated hydrochloric and sulfuric acids have low oxygen solubilities and ionize very little. Consequently they are not as corrosive as solutions of moderate concentration on metals which must be depolarized by oxygen.

(b) *Weak acids,* found in foods and soils, could corrode as fast as the strong acids if enough oxygen were supplied, but usually there is little oxygen in places where they occur.

(c) *Oxidizing acids,* such as nitric and chromic, supply their own oxidizing agent, and keep the metal surface depolarized. Therefore, metals cannot be used in contact with oxidizing acids unless a protective film is formed (passivation).

ALKALIES   Corrosion by alkalies is generally not as fast as by neutral and acid solutions, because the hydrogen-ion concentration is reduced, and because the hydroxides produced by corrosion are insoluble up to a certain value of alkalinity. Zinc and aluminum hydroxides, for instance, become soluble around $pH = 12$. Ferrous hydroxide is insoluble in a sodium hydroxide solution to $pH = 14$. Increasing pH reduces the corrosion rate unless the solution becomes alkaline enough to dissolve the protective hydroxide coating.

* A gram mole (or gram-molecular weight) is defined as a weight in grams equal to the molecular unit weight of the substance. A gram mole of H_2O is, therefore, $2 + 16$, or 18 grams.

SALTS   The action of salt solutions depends upon the solubility of the corrosion products formed. The chlorides, sulfates, bromides, and fluorides are quite soluble and tend to be very corrosive. The silicates and carbonates are less soluble and protect the metal surface, unless local concentration cells are set up.

Sea water contains fairly large concentrations of chlorides and sulfates of sodium and potassium, which form soluble corrosion products and increase corrosion.

ATMOSPHERIC CORROSION   The earth's atmosphere contains more oxygen than can take part in corrosion, but the quantity of water and carbon dioxide vary with the climate. Water can be condensed in drops from humid air by contact with cold surfaces. Water can also be absorbed from the air at less than 100 per cent humidity by many corrosion products. The average humidity, below which no absorption occurs is:

Corrosion Products of	Relative Humidity
Copper	100
Nickel	85
Iron	65

Chlorine compounds are present near sea water, but are at very small concentrations 5 or 10 miles from the sea. Sulfur compounds released mainly by modern fuels make the atmosphere in industrial areas particularly corrosive.

Dust particles from the air can form oxygen concentration cells by limiting the diffusion of oxygen to a metal.

SOILS   The corrosivity of soils varies with the locality because of differences in soil texture, acidity, oxidizing agents, moisture content, and temperature. Sulfur and sulfur compounds are present in decaying matter, natural springs, and natural gases and oils, and these compounds are particularly harmful. Hydrogen-sulfide-depositing bacteria may also be active in certain regions where the soil is free of oxygen and contains organic compounds and sulfates to support the life of the bacteria. Much work has been done on determining the effect of various types of soils on corrosion of pipes and conduits, and the effect of protecting materials for them.*

5.12   INFLUENCE OF DEPOLARIZATION

Hydrogen films are removed from the cathode in neutral and alkaline solutions mainly by depolarization of the hydrogen with oxygen.

* See "Corrosion in Soils," LC-689 United States Dept. of Commerce, Natl. Bur. Standards, Washington, 1942.

Absence of oxygen in the solution will therefore usually cause slow corrosion for neutral and alkaline electrochemical cells, but it will have little effect on corrosion by strong acid solutions since such acids do not usually dissolve very much oxygen. Consequently, unless a protective film is formed on the anode (anode polarization), the following factors will be important in determining the rate of hydrogen removal from the cathode and the rate of corrosion in neutral and alkaline cells.

(a) The concentration of oxygen in the solution as a whole, which is affected by temperature, presence of other dissolved substances, area of the corroding solution in contact with air, and actual humidity of the air.

(b) The diffusion of fresh electrolyte through protective metal coatings, which depends upon their porosity.

(c) The flow of the solution which renews the oxygen supply in the metal region. This is affected by convection, temperature, external agitation, depth of immersion, viscosity, etc. Flow or agitation also increases corrosion by wiping the atomic hydrogen from the cathode and even certain protective films from the surface of the anode.

Besides the above effects, solution flow is also important because of the formation of concentration cells. Areas shielded from the solution by cavitation, foreign particles, cracks, seams, etc., are likely to set up such cells, causing localized corrosion at these areas.

5.13   INFLUENCE OF CORROSION PRODUCTS

Corrosion products, as well as materials in the corroding solution, can form a protective film on the surface of a metal. With passivation, discussed previously, this film is extremely thin. Other coatings may be of substantial thickness. When such films are impermeable, they reduce corrosion. But if the film or coating is irregularly distributed and is cathodic to the metal, a galvanic cell will result and corrosion will be accelerated in adjacent areas. Porous coatings make the underlying metal more anodic by exclusion of oxygen (oxygen-concentration cell) and thus accelerate local pitting.

Solutions that are quiescent may increase in OH ion concentration next to the metal as the H ions are removed, and this more alkaline solution may act as a buffer to limit corrosion or hasten the formation of protective coatings.

5.14 INFLUENCE OF DURATION OF EXPOSURE

When a metal is exposed to corrosive media for a long period, its rate of corrosion may change with time. If the corrosion is uniform over the surface (single-metal corrosion), the initial rate is usually much higher than the final rate. If life expectancy is long and the corrosion factors are invariant, design should be based on the final rate.

In localized corrosion, the rate of pitting, contrary to the above, may actually be increased with time by formation of galvanic and concentration cells. Factors that assist the formation of these cells must be controlled or their effects must be estimated in designing for suitable life under these conditions.

When vibration is present in the environment, the simultaneous action of corrosion and alternating stress may cause *corrosion fatigue*. Corrosive attack apparently causes a small pit, and the applied load sets up a stress concentration at the base of this pit. This concentration of stress acts in the same manner as mechanical stress raisers in reducing the fatigue strength. Under the continuing action of corrosion there can be no final endurance limit.

Repeated cleaning, as by abrasion, removes the corrosion products, and thus lessens corrosion by eliminating the galvanic and concentration cells set up by these products. Railroad rails, for instance, show more corrosion when idle than when in normal use.

Corrosive Behavior of Common Metals and Alloys

5.15 GENERAL

The multitude of metals and alloys available to the designer, and the equally large number of corrosive environments, make it impossible to give recommendations for specific applications. To do so would require a full knowledge of *all* the requirements, and even then it might be difficult to predict accurately the rate of corrosion and the degree of localization. One needs only to note the apparent disagreement of many recorded data on corrosion resistance taken in both the laboratory and the field to appreciate the necessity for determining very accurately the influence of the many factors that may be involved.

In so far as comparison with similar cases can be used as a basis for choosing materials, Table 5.4 and the following discussion may be

Table 5.4　Relative Corrodibility

Class of Material	Maximum Safe Temp. for Good Service, °F			Fruit, Vegetable Juices	Dairy Products	Other Food Products	Acids Moderate Concentrations 5 to 15%				
	Oxidizing gases	Reducing fuel gas	Sulfur-rich gas				HCl	H_2SO_4	HNO_3	Acetic	Phosphoric
Low-carbon steel, open-hearth											
iron or wrought iron	800			P	P	P	P	P	P	P	P
Copper steel	800			P	P	P	PF	F	P	P	P
Cr-Cu-Si steel											
Hot galvanized iron and steel				P	P	P	P	P	P	P	P
Calorized iron and steel	1600	1600	1600								
Gray cast iron	700			P	P	P	P	P	F	P	P
High silicon iron				G+	.	.	F	E	E	G	G
Nickel cast iron			.				P	F	F		
Ni-Cr-Cu cast iron *				F			FG	FG	G		
Chromium cast iron	1800	1800	1800								
Nickel steel											
Low nickel	840			P	P		P	P	P	P	
High nickel	930			F			FG	G	F	P	
Chromium steels											
4 to 6% chromium	1200	1200	1200	P			P	P	P	P	P
12 to 14% chromium	1400	1400	1400	G		G	P	P	G	G	F †
16 to 18% chromium	1600	1600	1500	G	G	G	P	P	G	E †	P
25 to 30% chromium	1900	1900	1800	E	G	E	P	P	E	F	G .
Chromium nickel steels											
8-20%	1600	1600					P	G	F	G	G
18-8%	1550	1550	300–1300	G	E	E	P	F	G	G	G
18-8%, 4% Mo							P		G	G	G
18-12%							P	F	G	G	F
18-35%	1900	1900	1900	G			P	G	P	P	F
25-12%	2100			G	E	E	P	P	G	G	F
26-24%	2100	2000		G	E	E	P	F	G	G	G
Silchrome steel	1500	1500		F			P	P	E	G	.
				E			P	P	E	G	.
Stellite	2000	2000		E	E	E	F	G	E	G	E
Commercially pure nickel	1300	2000	P	G	GE	GE	G	G	P	G	G
Nickel alloys											
Monel metal	900	2000	P	G	FE	FG	FG	G	P	G	G
Nichrome 60-15%	1475	2100	P	G			F	F	F	G	G
Inconel, 14% chromium	2000	2000		E	E	E	—				
80-20% nickel-chromium				G			F	G	P	G	G
Hastelloy				E	G	G	G	FG	G	G	E
Commercially pure copper	.	..	.	FG	P	F	F	FG	P	FG	FG
Copper alloys											
Red brass	..	..	.	FG	P	P	P	FG	P	FG	FG
Tobin bronze	.	..	..			.	P	F	P	F	F
Phosphor bronze	.	.	.	P	P	F	P	FG	P	FG	FG
Silicon bronze	..	..	..	G	P	.	F	G	P	G	G
Aluminum bronze	..	.	..	FG	P	.	P	FG	P	FG	FG
Nickel silver	..	..	.	G	P		F	G	P	G	G
Admiralty metal	..	.	..	FG		..	P	FG	P	FG	FG

* Alloys added should be increased with thickness of section.　　P = Poor.
† E at low and P at high concentrations.　　F = Fair, only to be used in temporary construction.

of Uncoated Metals and Alloys

Alkalies, 5 per cent	Salt Solutions, Moderate Concentrations			Hot Sulfite Liquor	Dye Liquor	Refinery Crudes below 400 F		Atmosphere		Water					
	NH_4Cl	$MgCl_2$	$MgSO_4$			Sweet	Sour	Seashore	Industrial	Domestic	Mine	Sea	Saline with H_2S	Brackish with NaCl	Wet steam
E	P	F	F	P		F	P	P	P	P	P	P	P	F	F
E	P	F	F	P	.	F	P	F	F	P	F	P	P	F	FG
								FG	FG	F	FG	FG			
P	P	P	PF					G	G	F	F	G	F	F	
				P	P	FG	FG	G	G	P	P	P			
G	P	P	P	P	P	F		F	G	P	P	P	F	F	F
E	G	G	G	P				E	E	E	G	E			
GE				P	P	F+	FG	F	G	F		F	F+	F+	
GE	F	F	F	F	F	G		GE	GE	G		G	G	G	G
								G	G	G	G	FG			
E	P	F	F					F	F	F	P	F	G	G	
E	F	G	G					E	E	G	FG	E	G	G	
G	P	P	F	P	P	G	G	FG	FG	FG	FG	FG	G	F	FG
E	G	G	G	P	F	E		G	G	G	FG	FG		FG	G
E	G	G	G	F	F	E	E	G	G	G	G	G		G	G
G	E	E	E	GE				G	G	E	G	G		G	E
				P		G		G	G	G	G	G			
	FG	E	E	GE	F	E	E	E	E	E	G	G	E	G	E
G	E	E	E	GE	G	E	E	E	E	E	G	G	E	G+	E
E				G		E	E	E	E	E	G	G		E	
G				P				E	E	E	FG	G			
G	E	E	E	GE	G	E		E	E	E	G	G	E	G	E
G	E	E	E	E	G	E		E	E	E	G	G	E	G	E
G					PG			G	G	F	F	F	F	F	F
E								G	E	E	E	F	E		
E	E	E	E	G	G	E	E	E	E	E	E	E	E	G	E
E			G	P	G			E	G	E	G	E	G	E	
E	E	E	G	P	E	F		E	G	E	PG	E	G	G	E
G	.			P				G	G	E	G	G			
								G	G		G	G			
E								G	G	E	G	G			
E	G	G	G	E	G	G	G	E	E	E	G	E	E	E	E
FG	.	.	..	F	FG			G	G	G	FG	G	P	.	G
P	..	..	..	F	FG			G	G	FG	FG	G	P	F	P
F	..	..	..	G	G	FG		G	FG	.	F	G	F	F	
FG	.	..	..	G	FG			G	FG		F	G			
FG	..	.		G	FG			G	G	..	FG	G			
FG	..				FG	G		G	G		FG	G	..	F	
G	..	.		.	FG			G	G		G	G			
P	..	..	..	..	FG			G	G		FG	G	..	F	

· Good, will give good service.
· Excellent, almost unlimited service.

155

Table 5.5   Electromotive Force Series

by A. E. Durkin and Carroll Seversike

Anodic End

1 Lithium
2 Rubidium
3 Potassium
4 Strontium
5 Barium
6 Calcium
7 Sodium
8 Magnesium and its alloys
9 Aluminum
10 Beryllium
11 Uranium
12 Manganese
13 Tellurium
14 Zinc
15 Chromium
16 Sulfur
17 Gallium
18 Iron (Fe^{++})
19 ⎡Galvanized steel [1]
20 ⎢Galvanized wrought iron
21 ⎢Al-Zn-Mg alloys (e.g.: Al-75S) [2]
22 ⎢Al-High Mg alloys (e.g.: Al-220)
   A⎨
23 ⎢Al-Low Mg alloys (e.g.: Al-4S)
24 ⎢Aluminum plus very low percentage of alloying constituents (e.g.: Al-53S)
25 ⎣Alclads
26 Cadmium
27 Al-Si-Mg alloys (e.g.: Al-356)
28 Al-Cu alloys (with or without small additions of Mg) (e.g.: Al-24S)
29 Al-Cu alloys (with or without small additions of Zn) (e.g.: Al-113)
30 Al-Cu-Si alloys (e.g.: Al-108)
31 Mild steel
32 Copper steel
33 S.A.E. 4140
34 S.A.E. 3140
35 Wrought iron
36 Cast iron

37 4–6% chromium steel, type 501 or 502 (active)
38 12–14% chromium steel, types 403, 410, 416 (active)
39 16–18% chromium steel, type 440 (active)
40 23–30% chromium steel, type 446 (active)
41 Indium
42 Thallium
43 Cobalt
44 Ni-resist cast iron
45 50–50 lead tin solder
46 17% Cr-7% Ni steel, type 301 (active)
47 18% Cr-8% Ni steel, types 302, 303, 304, 321, 347 (active)
48 23% Cr-14% Ni steel, type 309 (active)
49 25% Cr-20% Ni steel, type 310 (active)
50 18% Cr-12% Ni-3% Mo steel, type 316 (active)
51 Hastelloy "C" (59% Ni, 17% Mo, 5% Fe, 14% Cr, 5% W, 0.1% C)
52 Lead
53 Tin
54 Iron (Fe^{+++})
55 Hydrogen
56 Antimony
57 Bismuth
58 Arsenic
59 ⎡Muntz metal (60% Cu, 40% Zn) [4]
60 ⎢Manganese bronze (66.5% Cu, 19% Zn, 6% Al, 4% Mn)
61 ⎢Naval brass (add. of ¾% Sn to Muntz metal)
   B⎨
62 ⎢Nickel (active)
63 ⎢60% Ni-15% Cr (active)
64 ⎢Inconel (78% Ni, 13.5% Cr, 6% Fe) (active)
65 ⎣80% Ni-20% Cr (active)

Table 5.5   Electromotive Force Series (Continued)

66	Hastelloy "A" (60% Ni, 20% Ni, 20% Mo, 20% Fe, 0.1% C)	87		Inconel (passive)
67	Hastelloy "B" (65% Ni, 30% Mo, 5% Fe, 0.1% C)	88		80% Ni-20% Cr (passive)
68	Yellow brass (58–70% Cu, 0.50–1.5% Sn, 0.75–3.5% Pb, balance Zn)	89		Titanium
69	Admiralty brass (71% Cu, 28% Zn, 1% Sn)	90		Monel (70% Ni, 30% Cu)
70	Aluminum bronze (add. of 2-2-¼% Al to 75% Cu-25% Zn alloy)	91		12–14% Cr steel, types 403, 410, 416 (passive)
71	Red brass (85% Cu, 15% Zn)	92		16–18% Cr steel, type 440 (passive)

66–71 bracketed with **B**

B group (66–71):
66. Hastelloy "A" (60% Ni, 20% Ni, 20% Mo, 20% Fe, 0.1% C)
67. Hastelloy "B" (65% Ni, 30% Mo, 5% Fe, 0.1% C)
68. Yellow brass (58–70% Cu, 0.50–1.5% Sn, 0.75–3.5% Pb, balance Zn)
69. Admiralty brass (71% Cu, 28% Zn, 1% Sn)
70. Aluminum bronze (add. of 2-2-¼% Al to 75% Cu-25% Zn alloy)
71. Red brass (85% Cu, 15% Zn)

72. Copper (-ic)
73. Oxygen
74. Polonium
75. Copper (-ous)
76. Iodine
77. Tellurium

C group (78–83):
78. Silicon bronze (1.0 to 3.0% Si) [5]
79. Nickel-silver
80. Ambrac (5.0% Zn, 20% Ni, balance Cu)
81. 70% Cu-30% Ni
82. Comp. G–bronze (88% Cu, 2% Zn, 10% Sn)
83. Comp. M–bronze (88% Cu, 3% Zn, 6.5% Sn, 1.5% Pb)

84. Silver solder
85. Nickel (passive)
86. 60% Ni-15% Cr (passive)

87. Inconel (passive)
88. 80% Ni-20% Cr (passive)
89. Titanium
90. Monel (70% Ni, 30% Cu)
91. 12–14% Cr steel, types 403, 410, 416 (passive)
92. 16–18% Cr steel, type 440 (passive)

C group (93–98):
93. 17% Cr-7% Ni steel, type 301 (passive)
94. 18% Cr-8% Ni steel, types 302, 303, 304, 321, 347 (passive)
95. 23% Cr-14% Ni steel, type 309 (passive)
96. 23–30% chromium steel, type 446 (passive)
97. 25% Cr-20% Ni steel, type 310 (passive)
98. 18% Cr-12% Ni-3% Mo steel, type 316 (passive)

99. Mercury
100. Silver
101. Lead (Pb^{++++})
102. Palladium
103. Bromine
104. Chlorine
105. Graphite [6]
106. Gold (-ic)
107. Gold (-ous)
108. Platinum
109. Fluorine

Cathodic End

Notes: (1) Members of Group A are listed relative to each other, but the position of the Group with respect to the group between chromium and ferrous iron is uncertain. The group, however, is listed correctly between zinc and cadmium.

(2) The heat treatment of Aluminum and its alloys has an effect upon their potentials. They fall in the aluminum group, however, regardless of the heat treatment.

(3) Indium, Thallium, and Cobalt are listed relative to each other, but their position relative to the stainless steels is uncertain. They are properly placed between aluminum and lead.

(4) The members of Group B are listed relative to each other, but the position of the group relative to ferric iron to arsenic is uncertain. The group is, however, properly placed between tin and copper.

(5) The members of Group C are listed relative to each other, but the position of this group with respect to Iodine, Tellurium and Mercury is uncertain. However, the group is properly placed between copper and silver.

(6) Graphite lies between lead and gold but its position relative to palladium, bromine and chlorine is uncertain.

Note: Select contacting combinations as close together as possible in this series. Keep dissimilar metals as far apart as possible and particularly avoid threaded connections between widely dissimilar metals. Avoid combinations where the area of the less noble metal is small; that is, use a more noble fastening for a less corrosion resistant part, like monel rivets on a steel tank instead of steel rivets in a monel tank. Insulate joints where possible. Paint both the noble and the less noble metal if paint insulation is used. When brazing, choose a brazing alloy more noble than at least one of the metals to be joined.

* Thomson Laboratory, General Electric Co., Lynn, Mass.

used for estimating the resistance of many common metals and alloys to a number of common corrosives. Where contact between dissimilar alloys or elements is involved, Table 5.5 may be used as a guide in choosing combinations which will have little galvanic action. The reader is cautioned to temper these general considerations in response to the factors already discussed. In large installations or for large production, it would be preferable to use these data as a guide to conducting pilot tests which assure the necessary life.

5.16 IRON AND STEEL

Under this heading are included cast iron, wrought iron, low-carbon steel, and low-alloy steel. From the standpoint of corrosion resistance, these metals (with a few exceptions) do not differ markedly; neither do they have superior corrosion resistance, since they were not developed for that purpose.

In water free from dissolved salts, the effect of acidity on the corrosion rate for iron is shown by Fig. 5.5. The diagram may be divided into three separate zones.

(1) The acid zone for pH less than 4.3. The corrosion decreases rapidly with increasing pH in this zone. Total acidity, rather than hydrogen ionization alone, determines the pH limit. Since the formation of molecular hydrogen controls the rate at which the corrosion proceeds, those factors which influence hydrogen overvoltage (surface finish, impurities, metal composition, solution velocity) are of importance. Surface films are of little protection.

(2) The neutral zone for pH between 4.3 and 10 (lower curve). In this zone the corrosion rate is medium and essentially constant, since

oxygen depolarization is the controlling factor. Conditions favorable for increasing the oxygen concentration in the solution widen this zone.

(3) The alkaline zone for pH greater than 10. Here the corrosion is slow and decreases with increasing alkalinity (pH). Presence of a protecting hydroxide film is the controlling factor rather than the decreased H ion concentration, since the plating of hydrogen on the metal would still occur faster than its depolarization with oxygen. [16]
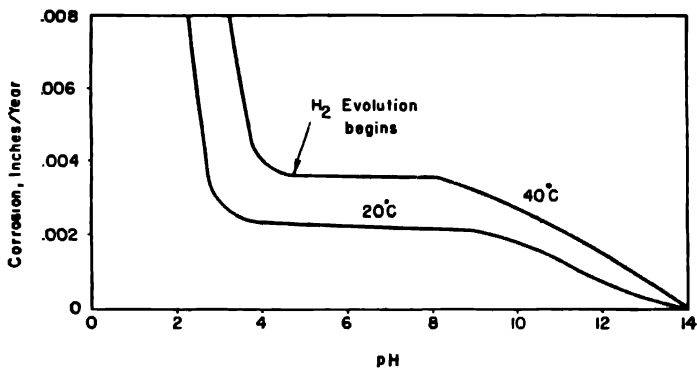

FIG. 5.5. Corrosion rate of iron and low-carbon steel versus hydrogen-ion concentration.

the solution is very quiescent and contains little oxygen, the alkaline zone may extend to lower values of pH. Dissolved salts also change the pH limit of this zone.

Ordinarily, iron and steel are attacked by all low pH acids, but the formation of insoluble ferrous sulfate gives the metals some protection from concentrated sulfuric acid. The formation of ferrous hydroxide accounts for the resistance of the irons and ordinary steels in alkaline solutions. But dissolved oxygen present will oxidize this hydroxide to ferric hydroxide in the neutral and slightly alkaline solutions, with the formation of the familiar brown-rust precipitate. Rust is not protective and, in fact, aids the formation of concentration cells by limiting diffusion of oxygen to the surface, thus causing pitting. This action is inhibited to some extent by the formation of lime scales and phosphate coatings (both of which are protective) from natural or treated waters. Exposure of cast irons to dilute solutions gives rise to a type of corrosion known as *graphitic corrosion*. This phenomenon was discussed in Sec. 5.9.

Caustic embrittlement is a type of corrosion that may occur when iron or steel is used in contact with sodium carbonate or sodium hydroxide solutions at high pressure. Steam boilers handling such waters sometimes develop cracks in riveted joints below the water-line. They have been associated with the removal of sulfides and oxides by the hot solution and cathodic hydrogen. The cathodic hydrogen apparently causes embrittlement by penetrating the metal and reducing the oxides or sulfides. The vapor thus formed at the grain boundaries causes a bursting pressure which may cause cracking.

For atmospheric exposure the presence of copper in iron or steel improves the corrosion resistance, probably owing to the formation of a tightly adherent rust and to reaction with sulfur in the metal.

5.17 CORROSION-RESISTING STEELS

This group comprises those high-chromium steel alloys that were developed primarily for resistance to corrosion. These steels are popularly known as "stainless steels" although, as emphasized in the previous discussion, no perfectly stainless metal has yet been found. In discussing these materials it is convenient to divide the group into five basic types, as follows:

(1) Twelve to 17 per cent chromium steel with high carbon (0.3 to 1.5 per cent C). Used chiefly for cutlery and small parts requiring a hard surface for wear resistance.

(2) Eleven to 14 per cent chromium steel with low carbon (0.06 to 0.13 per cent C). Used for structural applications requiring good corrosion resistance.

(3) Sixteen to 20 per cent chromium steel with low carbon (0.06 to 0.15 per cent C). Used chiefly for ornamental purposes and resistance to oxidation to 1650 F.

(4) Twenty-five to 30 per cent chromium steel with about 0.25 per cent C. A nonheat-treatable alloy used chiefly for resistance to oxidation at elevated temperatures.

(5) Eighteen to 26 per cent chromium and 8 to 21 per cent nickel steel with 0.06 to 0.15 per cent C. The maximum resistance to corrosion of these types.

The improved corrosion resistance of this class of steels is caused by the formation of a protective film due to the presence of chromium. This film may be formed in air, but frequently it is artificially accelerated by a passivating dip into dilute nitric acid. This dip removes the free iron at the surface of the part and also forms a pro-

tective film. If the film is broken in service, it will usually heal if oxygen is present.

The group as a whole is resistant to nitric acid, and all but Type 1 are used in the nitric acid industry. They are resistant to the weak acids, but are attacked by the strong nonoxidizing acids, hydrochloric and sulfuric, of all concentrations. Chloride solutions will also break down the protective film and cause corrosion. No general rule can be set down for the resistance to mixed oxidizing and nonoxidizing acids. The resistance to attack by alkalies and organic substances is very good. The resistance of various chromium steels to corrosion by petroleum products is compared with that of plain carbon steel in Fig. 5.6. Nickel added to chromium steel, as in Type 5, increases the alkaline resistance and improves the resistance to all neutral solutions and acid attack.

In conjunction with the formation of the protecting film, it should be mentioned

FIG. 5 6. Resistance of various chromium steels to corrosion by petroleum products compared with that of plain carbon steel. (*Speller, Corrosion, Causes and Prevention, McGraw-Hill Book Co., 1935, p. 131.*)

that the finish is important to the corrosion resistance. *The better the finish, the greater the resistance to corrosion.*

"Stainless" steels of austenitic types, 4 and 5, are subject to local failure by intergranular corrosion if improperly heat treated. The improper treatment consists in heating the solution-quenched specimen within a critical range from 900 to 1400 F, even for only a few minutes. Chromium carbides are precipitated on the grain boundaries by this treatment. These carbides rob the adjacent metal crystals of their chromium and thus remove their resistance to corrosion. The chromium-impoverished metal along the grain boundaries is readily attacked by strongly corrosive agents. When these alloys are made susceptible to this attack, they are said to be "sensitized." They can be restored to the original condition (stabilized) by reheating to 1900 to 2000 F and quenching in water so as to reabsorb the carbides and retain chromium in solution.

An intermediate grade of corrosion-resisting steels is formed by those alloys containing 4 to 6 per cent chromium. Although their re-
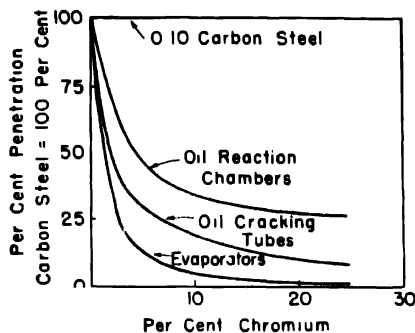
sistance compared with the above types is small, it is still four to six times that of low carbon steel for corrosion in air and at somewhat elevated temperatures, and may prove the more economical in certain applications, particularly those of the oil industry. They offer considerable oxidation resistance to 1200 F.

Clad metals (e.g., Pluramelt) have been developed to take advantage of the corrosion properties of the stainless steels and the low cost of low-carbon steel. These metals consist of a thin sheet of chromium steel on one or both sides of a low-carbon steel plate.

5.18   COPPER AND COPPER-BASE ALLOYS

From the position of copper in the electromotive force series, it would be expected to have excellent resistance to corrosion. This is true, in general, both for copper and for its alloys.

The corrosion of copper, except for a few special cases, differs from that of the other metals studied in that its corrosion resistance depends on its limited solubility and reasonable hydrogen overvoltage, rather than on the formation of protective films. Thus the corrosion tends to proceed by depolarization of hydrogen; consequently, the control of oxygen is important in acid corrosion as well as in corrosion by neutral waters and alkalies.

For this reason, the metal and its alloys, with the exception of the brasses, are fairly resistant to the nonoxidizing acids (sulfuric, phosphoric, etc.) and to many salts and industrial waters of limited oxygen content. And for the same reason they are, in general, attacked by the oxidizing acids and their salts, since no passivation occurs. Ammonium hydroxide corrodes them easily, but usually they are resistant to alkalies of moderate concentration at normal temperatures.

The red brasses (85 Cu, 15 Zn) are not greatly different from copper and the bronzes in corrosion resistance to dilute acids. The yellow brasses (65 Cu, 35 Zn) are of considerably less value. Yellow brasses are subject to dezincification and corrosion cracking (see Fig. 5.7), which have already been described. The presence of 1 per cent tin in the brass will reduce the tendency for dezincification, especially in neutral and slightly acid solutions. Ammonia and industrial (SO_2) atmosphere are quite active in causing corrosion cracking. It is interesting to note that both forms of corrosion can be substantially reduced by using red instead of yellow brass.

Corrosion of insulated copper wire is often attributed to the characteristics of the insulation. Rubber insulation and tapes may con-

tain sulfur or acids, and other insulating materials are often capable of forming acids if they absorb moisture. With all, the prevention of water penetration is of primary importance when limiting this type of corrosion.

FIG. 5 7. Photomicrograph of season crack in aluminum brass (76 Cu. 22 Zn. 2 Al). Note that the crack is transcrystalline in the body of the material, and intercrystalline (the usual form) near the edge at the right.

5.19 ALUMINUM AND ITS ALLOYS

The corrosion resistance of aluminum is good in nearly neutral waters, atmospheres, and salts, and also in the oxidizing acids such as nitric, because it forms a protective oxide film. In air this film is of the order of 0.000001 in. Since strong nonoxidizing acids and strong alkalies will remove this film, and chloride salts will penetrate it, corrosion in the presence of these solutions will be rapid.

Alloying or metallic contact with even the most noble (cathodic) metals will not produce galvanic cells of importance in weak electrolytes, or in industrial and rural atmospheres, but copper, nickel, tin, and, to some extent, zinc have been found very corrosive in humid sea atmospheres. Normal atmospheres permit contact with zinc- and cadmium-plated iron surfaces.

Duralumin is subject to intergranular crystallization if aged at much above room temperature. Uniform surface elastic stress seems to promote this condition. Duralumin also has a markedly reduced fatigue strength in corroding conditions. In order to take advantage of the higher strengths it offers and still to provide suitable corrosion resistance, Duralumin has been made with a pure aluminum surfacing, and in this form is called Alclad, Pureclad, etc. When Duralumin

rivets are used with a clad sheet, the corrosion is limited to a small amount on the sheet near the rivet.

Aluminum may be protected by artificial formation of the oxide film (anodizing) by plating oxygen on the surface in an electrolytic cell having a suitable electrolyte, the most common of which is sulfuric acid. The oxide thus formed will have a depth of 25 to 500 times that which occurs in air. A cheaper but somewhat less effective oxide coating can be formed by a chemical dip treatment.

5.20   MAGNESIUM AND ITS ALLOYS

Magnesium readily combines with oxygen at low temperatures, forming a protective oxide that makes the metal serviceable for unpolluted atmospheres. Attack by acid phosphates, bichromates, or dilute chromic acid is resisted, but performance in the presence of salt, salt spray, or industrial atmospheres is poor. Presence of manganese improves the resistance to sea water.

Since magnesium-base alloys have the ability to form a protective film in hydrofluoric acid, they are used for handling that acid in all but the most dilute concentrations. Resistance to other acids is very low. The resistance to alkali solutions by comparison is quite good

From the electromotive force series it is apparent that magnesium should set up powerful electrochemical cells with most any other metal. This tendency is so strong that copper and nickel will prove damaging if alloyed in the metal at concentrations over 0.1 per cent. The couple with zinc and mercury is considered serviceable, mainly because the smaller difference in solution pressures and the higher hydrogen overvoltage of these metals reduce the corrosion. Thus magnesium can satisfactorily be put into contact with galvanized iron, although contact with aluminum under corrosive conditions is harmful.

If the corrosion resistance of magnesium is to be improved, chromic treatments and painting are the only recourse; plating and anodic oxidation are not beneficial.   –

5.21   ZINC AND CADMIUM

The largest industrial application of zinc is for the galvanizing of iron. Since zinc is anodic to iron (see Table 5.1), the zinc coating will corrode first in the presence of corrosive media, thus prolonging the life of the iron beneath. This means that discontinuities in its surface do not hasten the corrosion of the metal beneath as would a coat of a more noble (cathodic) metal.

The life of galvanized parts is also increased by the tendency of the zinc surface to form a protective film (oxide or oxycarbonate), particularly under *alternate* wet and dry atmospheric exposure. The alkaline resistance is also enhanced by the formation of a protective film (hydroxide), but at a pH of 12 or higher this film dissolves and the zinc corrodes rapidly.

Strong acids (as found in industrial atmospheres) will also attack zinc; but gasoline, grease, anhydrous alcohol, soap, and soap pastes are essentially inert to zinc.

Cadmium is similar to zinc in its corrosive properties and uses. The resistance of cadmium to attack by industrial atmospheres, strong acids, and very strong alkalies ranges from 100 to 50 per cent of that of zinc under various conditions. Since the hydroxide of cadmium is not as soluble as that of zinc, the cadmium as a plate on iron has longer life in normal alkaline solutions. For underwater exposure, galvanizing is considered better than cadmium plating because greater thicknesses can be used at lower cost. The appearance of cadmium plate had long been superior to that of electrolytically deposited zinc, but progress in applying zinc has made possible bright finishes which retain their luster for a considerable time.

5.22 NICKEL AND NICKEL-BASE ALLOYS

Although the position of nickel in the electromotive-force series would indicate that it would corrode more than copper, the corrosion resistance of these two metals actually is nearly the same, and occasionally it overlaps. Since nickel is the more costly and least abundant, the choice usually rests with copper or its alloys if they are not unsuited. Corrosive applications in which nickel finds greatest use are: (1) the handling of alkalies and (2) resistance to some nonoxidizing acids.

Hydrochloric acid is resisted by nickel and Monel when in low concentrations. Alloys with molybdenum and iron (Hastelloy A and B) are used for handling hydrochloric acid when no oxidizing agents are present. Chromium is added for good resistance, even when oxidizing agents are present. An alloy with either chromium (Illium) or silicon (Hastelloy D) is used for handling sulfuric acid solutions.

5.23 OTHER METALS

Lead. The outstanding application of lead is in the sulfuric-acid industry. The metal has been found to form a protective film by contact with that acid, and thus is suitable for withstanding further at-

tack. Lead coatings or sheathings have also been used widely for protection against weather and corrosive industrial atmospheres, for protecting underground telephone and telegraph cable systems, and in the handling of a number of corrosive chemicals.

Tin. Tin is used somewhat as a protective coating for more noble metals. Because of its poor physical properties and higher cost, it is seldom used in the form of a base metal. Its resistance to the weak acids and neutral solutions is rather good, but it is rapidly attacked by alkaline solutions, especially at elevated temperatures. An important use for tin is in the coating of sheet steel to be used in making tin cans.

Silver and Other Precious Metals. These metals are important to the study of corrosion because of their application to the chemical industry. Silver is perhaps the most used. Some of its applications are in handling acetic acid, acetate rayon, food products, e.g., syrups, jams, and jellies, in photographic emulsions, and in the manufacture of chemically pure chemicals. Frequently, the equipment may use the metal only as a lining, but the high scrap value of parts makes it practical in the long run to use parts made entirely of silver.

Titanium. Titanium containing traces of nitrogen and oxygen is brittle. In this condition its corrosive behavior is much like 18-8 stainless steel. It is passivated by nitric acid but is attacked by cold dilute hydrochloric, sulfuric, and hydrofluoric acids. Titanium is also attacked by water at 1475 F but withstands oxygen to 1100 F. At higher temperatures it will reduce all known oxides and reacts with the halogens, sulfur, and ammonia. It is almost completely resistant to salt-water attack, and developments in the winning and refining of this metal will promote and extend its use in industry.

5.24   CORROSION TESTS

No single "accelerated" corrosion test has been found that will correlate with service exposure. The intensification of corrosive conditions to cause severe corrosion in a short period of time apparently gives a completely changed nature to the test environment. More important, perhaps, is the wide variance of metal behavior in the multitude of different environments, so that even a few different accelerated tests cannot be interpreted in general terms for the typical range of service conditions.

The tests that are conducted in the laboratory serve as control tests to assure uniformity of product, and as special property tests to determine susceptibility to special types of corrosion. This latter

type, in particular, seems a promising direction for further development.

The typical laboratory tests are:

(1) *Total-immersion test,* especially in acid baths, to determine comparative corrosion resistance. Velocity in the solution, temperature, aeration, concentration, and surface are important variables that must be controlled to make the test reproducible.

(2) *Intermittent-immersion test* for comparing corrosion resistance in a wide variety of media. This test is also useful for control of production lots of certain alloys.

(3) *Salt-spray test,* in which specimens or parts are inclined in a chamber and subjected to a fine spray or fog of salt solution at a specified temperature. This test is somewhat similar to marine exposure but does not reproduce all marine conditions. It is considered an arbitrary performance test, in which the extent and nature of the corrosion serve as a measure of quality. The porosity of cathodic coatings on steel is indicated qualitatively by the number of rust spots per unit time. Thickness of anodic coatings like zinc and cadmium on steel is indicated by exposure time before rusting. Validity of the test depends on correlation found in actual service conditions.

(4) *Humidity-chamber test,* in which a part or specimen is subjected to high humidity at a controlled temperature. Condensation cycles may be imposed to simulate this condition, which occurs in the hotter climates. This test is often used in comparing paint and primer coatings.

(5) *Special-purpose tests* for evaluating tendency of a few fabricated metals toward characteristic corrosion such as dezincification, impingement corrosion, intergranular corrosion, and stress-corrosion cracking.

To attain a more representative test for certain environments, field tests are conducted by subjecting panels to exposure under various atmospheres, in various soils, or to marine immersion. Several duplicate panels are used to obtain representative average results.

5.25 METHODS OF IMPROVING CORROSION RESISTANCE

The various methods that may be employed to lengthen the life or reduce the corrosion of a metal part may be classed under the following headings:

(1) Improvement in the corrosion resistance of the metal.

(2) Changing the environment so that it will be less corrosive.

(3) Isolating the metal from the destructive environment.

Under heading (1) is selection of metals that will have good resistance to the particular environment. The previous discussion should facilitate this selection. Perhaps placing an insulating gasket between two different metals in contact, or coating with paint or heavy
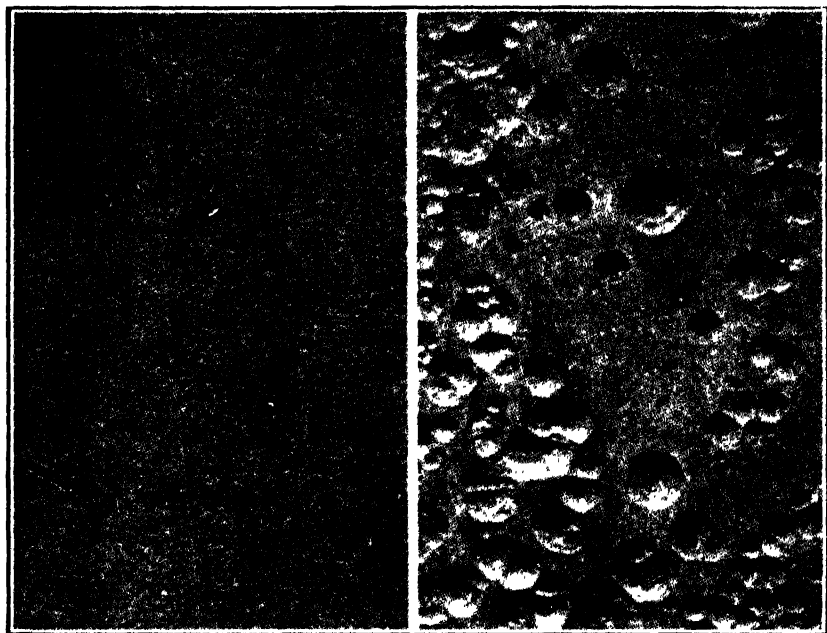

Fig. 5.8. Corrosion of plain carbon steel. *Left,* uniform surface corrosion. *Right,* pitting. Both about actual size. (*Courtesy, Research Laboratories, Carnegie Steel Corp.*)

caulking compound, thereby destroying the galvanic cells, could also be considered in this class.

Under heading (2) are dehydration, deoxidation, electrolytic cathodization, and use of inhibitors.

When a part in the atmosphere must resist corrosion, methods of dehydration (removing moisture) will be useful, since the electrochemical cell depends on an aqueous solution for its action. Dehydration may be brought about by absorbing all the water present, as with lime, by driving off the moisture with heat, by dehumidification of the air with refrigeration, or by preventing the condensation or dripping of moisture on the surface by shielding.

Deoxidation is used to reduce the corrosion in closed conduits, containers, etc. It is effective on those corrosion reactions (particularly those on the anodic metals by dilute acids and neutral and alkaline solutions) that depend on oxygen depolarization. For this purpose, specially designed deaerators are constructed and situated so as to remove most of the air in the fluid entering the conduit. The gasoline and oil pumped in pipelines are deaerated before they are pumped into the line. Deaeration will be very objectionable where the protection of the metal depends on maintenance of a passivated film by continuing oxidation.

Electrolytic cathodization essentially consists in eliminating the driving force of the electrochemical cell by applying externally a counterpotential. It has been used in limiting the corrosion of underground pipes in particularly acid soils.

Pipes are often corroded because of potentials set up in the surrounding earth. Streetcar lines which use the rails as conductors often set up potentials in the soil and cause nearby pipelines to carry part of the current. Very long pipelines also carry currents that may originate from galvanic action or from earth currents due to terrestrial magnetism. But, whatever the source of the current in a pipeline, it is corroded at the section that acts as an anode. A potential from an external source applied so as to make these sections cathodic will tend to stop corrosion, but it may have an opposite effect upon other pipes nearby.

The use of inhibitors is of major significance in equipment such as steam turbines, where a corrosive, such as the lubricating oil, is to be in contact with a metal surface for a long time under optimum conditions for corrosion (elevated temperature, motion, aeration, moisture from condensate, etc.). Inhibitors for this application are of two types: antirust and antioxidant. The antirust inhibitor really is for the purpose of wetting the surfaces of bearings and thus, by excluding moisture, limiting rusting. The antioxidant inhibitor is for the purpose of removing the free oxygen so that it will not combine with the oil. Other types of inhibitors are used to treat natural waters used in boilers, pipelines, etc.

Under heading (3) are such operations as passivation; plating, cladding, and painting; slushing; and evacuating.

Plating and cladding will reduce the corrosive rate under certain conditions by self-sacrifice corrosion, or by presenting a material that forms a protective film for the environment. The various materials used and the methods of applying them will be discussed in a later

chapter.   Painting is the most common and one of the cheapest methods of isolating the part from the environment, but for long service it must be renewed.   It cannot be expected to withstand an extremely corrosive combination of service conditions.

Slushing compounds may be of two fundamentally different kinds. (1) They may be of polarizing nature, which means they will *drive* the moisture away from the surface, or (2) they may be mere films (e.g., no-oxide grease) which prevent contact of additional corrosive with the metal but *will not* stop corrosion if corrosion products (such as concentration cells) are trapped on the surface.   There are many polar slushing compounds available commercially, having such trade names as Tectyl, Rust Ban, and Nox Rust.   Slushing compounds should not be oxidizing in nature, or they themselves will serve as the corrosive if any moisture (even distilled) is trapped by them.

Evacuation consists in building an enclosure around the article that is to be resistant to corrosion, and then evacuating all corrosive media from the enclosure.   With some applications it may be necessary only to remove one constituent, say the oxygen, or the moisture. An excellent example of this method is the totally enclosed type of refrigerator unit containing a compressor, a condenser, and an evaporator, filled with SO_2 or a Freon, but essentially no oxygen or moisture.   Another example is use of a silica-gel dryer in a sealed package.

5.26   SELECTING METALS FOR CORROSIVE APPLICATIONS

Material may be considered corrosion resistant or not, depending on what is expected of it.   Three different criteria of corrosion resistance are: (1) Avoiding contamination of such products as foods; (2) preventing leaks of closed containers or conduits; and (3) maintaining strength and other original mechanical properties so that the structure will not be weakened excessively.

Factor (1) was not considered at length because it involves a separate study in itself.   However, it and the other two factors are the criteria on which the choice of corrosion-resistant metals must be based.   Counterbalancing these criteria at all times must be the economic estimates of the *ultimate* cost of the apparatus.   In certain instances it might be considered good business and sound engineering to use an inferior metal with the expectancy of replacing it during the service life of the entire apparatus.   Sometimes periodic maintenance such as cleaning, polishing, replating, and repainting may prove more economical than the price of a metal that would have the corrosion-resistant properties to give the life without maintenance.   In other

instances, maintenance and/or replacement of an inferior metal may be far more costly through complaints, loss of good will, risk to life, etc., than the additional cost of the better-suited material.

Tarnishing

5.27 NATURE OF TARNISHING

The usual continuous tarnish films developed on metal surfaces exposed to air at room temperature are oxides and sulfur compounds. The oxides formed are generally invisible, although on polished surfaces they tend to create a dull appearance. The sulfur compounds are produced by sulfur in the atmosphere from fumes of industrial, domestic heating, and transportation equipment and they usually have color. The color produced by the sulfur compounds and the dulling effect of oxides serve to disfigure such products as architectural trim, appliances, and utensils, which thus require considerable maintenance to retain their original appearance.

At elevated temperatures, such as in furnace atmospheres, turbines, jet engines, and oil-refining equipment, oxides formed often pass through several orders of interference colors. The straw-brown and the blue surface colors of tempered steel are well-known examples of high-temperature oxidation. Since the rate at which oxidation occurs increases with temperature, oxide formation at elevated temperatures may be sufficient to reduce the strength of components in a few months or years to the point where fracture under applied load is possible. Alternate heating and cooling or mechanical abrasion may cause the oxide formed to flake off, leaving the underlying metal exposed for fresh attack. This condition accelerates the "burning away" of the metal and further hastens the potentiality of failure due to insufficient strength.

Tarnishing is therefore an important property in engineering application of metals. At low temperatures, where rates are low, it may mar appearance and require much domestic maintenance. At high temperatures it may involve serious "burning away" of products, with resultant replacement expenditure.

5.28 TARNISHING RATES

Since tarnishing produces an adherent film of corrosion products on a metal surface, the rate of tarnishing is usually expressed in terms of the gain in weight per unit time. When the film is larger in volume

than the equivalent metal consumed, the film will usually be continuous and protective. When the film has smaller volume than the reacted metal, the film is usually porous and nonprotective. The *initial* formation of either type film usually increases by weight linearly with time. If the film is porous this relationship is extended in time; if protective it is depressed. The growth of porous films may reach a decreasing rate as thickness increases and will usually continue at the new rate linearly with time (see Fig. 5.9). The growth of
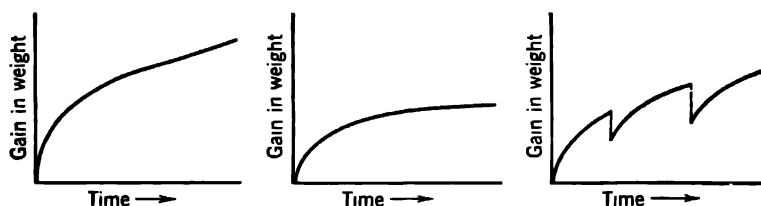
Fig. 5.9. Typical types of tarnish formation. *Left,* porous film that reaches linear rate after initial period. *Center,* nonporous film that reaches parabolic rate after initial period. *Right,* tarnishing at parabolic rate with simultaneous spalling.

a nonporous film usually decreases in rate as the thickness increases. The weight gain for many metals very nearly follows a parabolic relationship with time, finally reaching a very low rate if the film is not disturbed (Fig. 5.9). Some metals oxidize at a rate that is proportional to the logarithm of time, especially at the larger film thicknesses and in the lower temperature range.

The parabolic relationship between film growth and time has been explained by the increased time for simple diffusion of reactant atoms through the nonporous film as the film increases in thickness. The work of C. Wagner indicates, however, that the action involved may be electrochemical rather than chemical, at least for this rate of growth. Experiment with the formation of silver sulfide on silver shows that diffusion of metal ions of silver outward through the film is more pronounced than diffusion of sulfur ions to the metal. Further examples show the diffusion of the larger ion of the compound-forming group to be negligible, and the tarnishing to occur more rapidly in the presence of water vapor or moisture. It therefore appears that tarnishing, like corrosion, may be considered to behave as an electrochemical phenomena although satisfactory extension of this idea to porous film growth and to logarithmic growth of nonporous films has not been made.

The rate of oxidation becomes a discontinuous series of small parabolas with time when the oxide is periodically lost by flaking or spalling (Fig. 5.9). Stress is chiefly responsible for this action. The unconstrained volume of oxide is usually a good deal greater (15 to 100 per cent) than that of the base metal. The freshly formed oxide film is thus placed in lateral compression which may cause blistering, shear cracking, or flaking (Fig. 5.10). The loss of a small section by this action exposes an equivalent area of fresh metal surface for further oxidation and a repetition of the cycle. Heating and cooling accelerate the break down of the film by imposing during cooling
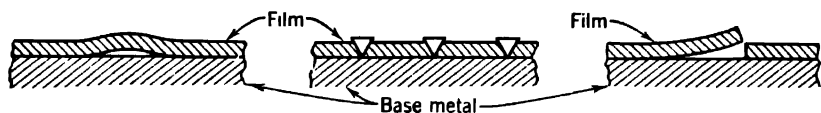
FIG. 5.10. Typical methods by which oxide films spall or break down. *Left,* blistering. *Center,* shear cracking. *Right,* flaking.

additional compressive stress through greater contraction of the metal than of the oxide film.

5.29   TARNISHING BEHAVIOR OF COMMON METALS

The choice of materials that will maintain their surface appearance without tarnishing becomes more difficult as the exposure increases in severity. For indoor use a number of common metals give suitable performance. Outdoor application reduces the number that will serve without maintenance, particularly in industrial and marine atmospheres. Plating and painting are frequently used as the most economical methods of utilizing a lower-cost metal and providing adequate appearance. The tarnishing characteristics of common metals are briefly reviewed in the following paragraphs.

Aluminum and Its Alloys. Exposure indoors in homes and offices ordinarily causes no more than a mild surface dulling of aluminum-base alloys, even after prolonged exposure. The alloys are also highly resistant to warm, humid conditions, with appreciable condensation of moisture if direct contact with porous material, settled pools of water, and corroding vapors is avoided. Sulfur compounds from industrial atmospheres are not effective in accelerating tarnishing.

At elevated temperatures aluminum and its alloys form a thin protective film, mainly of oxide, but resist atmosphere attack in the

presence of water to 700 F. Internal oxidation of some of the alloys may occur above this temperature, sulfur dioxide aiding this action and carbon dioxide inhibiting it. Steam causes formation of white corrosion product which is protective to 350–500 F.

Copper and Its Alloys. Pure copper exposed to the atmosphere slowly develops a thin protective coating of green tarnish but otherwise resists atmospheric attack. This tarnish is the basic sulfate, sometimes with some carbonate and wind-borne material, and at the sea-board it may be accompanied by the oxychloride. Brasses are similar to copper in tarnishing. The color of copper-tin alloy tarnish depends on the atmosphere. Sulfur-bearing atmospheres produce greenish-black and black films. Bright-green films form in coastal regions, and reddish-brown films predominate in dry rural regions. Alternate layers of red and green have been found on buried bronzes, apparently formed by action of the red cuprite (primary product) with moisture and carbon dioxide to produce the green product. Nickel-copper alloys will remain reasonably bright indoors and in outdoor exposure free from sulfur. Sulfurous atmospheres produce a brown or green film. The effects of weathering in marine and mild industrial atmospheres are generally not unattractive.

At high temperatures an oxide scale forms on copper, according to the parabolic rate after a temper-film thickness has been reached nearly at logarithmic rate. Below 1050 F the red cuprous oxide formed at the metal surface has a thin outer layer of black cupric oxide. Above this temperature the black oxide does not form and a cuprous oxide eutectic develops at the grain boundaries. The alloys rich in copper form these same oxides, but scales can form on these alloys in atmospheres that are not tarnishing to copper itself. Alloys less rich in the base element usually form no copper oxide, although nickel-copper is an exception. Oxygen-bearing copper should not be heated above 800 F and then for only short periods if in a hydrogen, water-vapor, or ammonia atmosphere. (See Chapter 8.)

Gold. Gold in pure form is not attacked by oxygen or sulfur compounds, although there is evidence that a minute oxide film forms and produces mild passivity. Tarnishing from sulfur compounds is generally not troublesome in alloys above 14 carat for normal applications and 18 carat for humid exposure. The low-carat jewelry alloys are vulnerable. White gold has good resistance to indoor tarnishing, and palladium additions give excellent tarnish resistance to dental alloys. Silver-gold alloys with 70 per cent or more gold have

negligible tarnishing. For outdoor exposure, gold leaf, the main application, should be 95 per cent pure to avoid tarnishing.

Magnesium and Its Alloys. Interior and exterior exposure of magnesium and magnesium alloys results first in production of a light-gray tarnish which gradually darkens to a dark gray. Analysis of this product shows the formation of the amorphous and crystalline hydroxide, then conversion of this phase to the carbonate with water of hydration. Moisture and carbon dioxide from the atmosphere are thus of importance in tarnishing of magnesium, but the tarnished product is not unattractive. At temperatures of 900 to 1060 F magnasium oxidizes according to linear rate and its oxidation increases rapidly with temperature. Aluminum and zinc in solid solution cause an increase in the oxidation rate. Water vapor also increases its rate, but sulfur dioxide and carbon dioxide reduce it.

Iron and Steel. It is well known that iron and its major alloy, steel, form a red rust upon exposure to the atmosphere. If bonded tightly the rust formation may prove protective in mild atmospheric conditions but it is generally objectionable. The growth normally follows the parabolic relationship and increases with temperature. Humidity, marine, and industrial exposure are more severe. Components of these materials are usually painted or plated for appearance, but attack may be reduced by adding alloying elements such as copper, chromium, aluminum, silicon, and nickel, which aid formation of an adherent rust. The austenitic chrome-nickel steels are resistant to indoor and outdoor exposures if free of surface scale, oxide, and free-iron contamination. They show no signs of permanent staining, even after long exposure, when kept clean of deposited dirt and salt particles, particularly in coastal exposure. Iron-nickel alloys do not retain their appearance as well as the austenitic Cr-Ni alloys. They acquire a rusty film which varies in thickness, color, and adherence with nickel content. The rust on alloys of 50 to 60 per cent nickel is loose and can be brushed off to reveal a bright surface. At high temperatures the oxidation resistance of chrome-bearing steel increases with chromium content, permitting service at 1200 F for the 4–6 per cent alloy and 2000 F for the 25 per cent alloy. Molybdenum additions are made to prevent temper brittleness at 900 F of the alloys containing 12 per cent or more of chromium. The nickel-chromium austenitic steels have a somewhat increased oxidation resistance over the plain chromium grades of equal chromium but are preferred mainly because of their higher strength. Sulfur and especially hydrogen sulfide tend to increase scaling at high temperature.

Nickel and Chromium. Nickel and nickel plating will remain reasonably bright indoors but become dull when exposed outdoors, through formation of a thin adherent corrosion product which usually is the basic sulfate. Nickel-chromium alloys similarly resist all types of atmospheres, with slight tarnishing and dulling upon exposure to industrial sulfurous conditions. Chromium platings must be applied in thicknesses up to 0.002 in. to eliminate porosity. At these thicknesses the process is more costly than applying a multiple subplate of copper and nickel, which is easy to plate and to polish, and depends on only a flash of chromium for its excellent tarnish resistance.

Nickel forms a green oxide at high temperatures. Various colors are developed with small alloying addition of other elements. The oxidation resistance increases with nickel content, and is reduced with increased temperature. Sulfur is harmful, carbon dioxide oxidizes nickel slowly, but carbon monoxide is reducing and causes brightening. Chromium, iron, and aluminum promote spalling, and vanadium, tungsten, and molybdenum aggravate it in the presence of iron.

Silver. Hydrogen sulfide tarnishes silver at room temperature with the formation of the black silver sulfide. Moisture is necessary for the reaction and it is accelerated by increased temperature. Alloying generally does not change the resistance of silver to sulfur compounds appreciably, although the 40 per cent palladium alloys show greatly improved resistance. Silver is not attacked by oxygen at temperatures up to 1500 F, but at 15 atmospheres pressure black oxide has been formed at 570 F. Oxygen will diffuse through silver rapidly above 750 F with subsequent embrittlement if exposed to hydrogen-bearing atmosphere at that temperature. Steam to 1300 F is not harmful, but sulfur, sulfur dioxide, and ammonia react at increasing rates with higher temperatures.

Zinc and Cadmium. In dry, indoor exposure a visible tarnish film forms slowly on zinc, generally starting at points of dust deposit. Over a period of time such films grow until the surface has lost much of its luster. Above 70 per cent relative humidity the film products appear to absorb moisture to stimulate a corrosion reaction often with formation of white products. Periodic condensation also accelerates corrosion, and contamination of the condensate in industrial atmospheres, particularly with sulfur, is even more serious. Outdoor reactions are of a corrosion type and depend on the moisture contact, frequency, atmospheric pollution, and rate of drying. Cadmium is similar to zinc, forming an adherent tarnish film on indoor exposure

at 55 per cent relative humidity or below. Corrosion occurs with periodic condensation, and it is aggravated by pollution with sulfur as SO_2 or SO_3. Cadmium-atmospheric tarnish generally is dark, with faint whitish spots.

5.30 CONCLUSION

The subjects of corrosion and tarnishing are complex and inexact. As a result, few general rules can be established for application to design problems. Instead, each material must be evaluated with respect to the particular service intended to determine its suitability. When the material dictated by other considerations must be protected from its environment, the means at the designer's disposal must be evaluated for all the environmental factors that can be deleterious in their effects. The engineer is urged to proceed cautiously when making specifications in this field. Full use should be made of service tests when this is possible. Information from the field and the laboratory should be carefully screened to assure that the circumstances are identical, if quantitative use is to be made of such data. For new applications where experience is limited, the services of experts in this field should be sought.

Review Questions

1. Define corrosion and tarnishing, and explain the major differences between them.

2. Is erosion a form of corrosion?

3. Name the three forms of attack that are typical mechanisms of corrosion.

4. Define "ion," "electrolyte," and "electrode potential."

5. (a) What is "depolarization," and by which methods can it be performed? (b) Which metals are hardest to depolarize?

6. Name three characteristics of a metal surface which might cause corrosion to be localized

7. What is pH, and how does it influence corrosion?

8. What determines the rate at which each of the three types of acids attacks a metal?

9 In general, do metals corrode faster in acids or in alkalies?

10. What is "sensitized" stainless steel, and how is it produced?

11. Does magnesium give good service when used in a humid atmosphere in contact with (a) aluminum, (b) galvanized iron, (c) copper?

12. Describe three methods that may be employed to lengthen the life or reduce the corrosion of a metal part. Give two examples of each method.

13. Name four typical laboratory tests for measuring the corrosion resistance of metals.

14. Continuous tarnish films on metal surfaces exposed to room air are composed usually of one of two compounds. Name them.

15. Name the three rates of tarnish film formation and indicate the types of films to which each applies.

16. What three types of film breakdown occur when oxide films have greater volume than the base metal?

6 ELECTRICAL AND MAGNETIC PROPERTIES

OF METALS

6.1 INTRODUCTION

In 1876 two dynamos were exhibited at the Centennial Exposition. One was a Gramme made in Belgium, and the other a Wallace made in America. Each was displayed supplying current to a single arc lamp. One, connected to a second dynamo, also drove a small pump. They were termed the curiosities of the exposition and received scant attention compared to the giant Corliss steam engine standing nearby. This engine packed 1000 horsepower in its 30-ft frame! It was in its heyday. Reciprocating engines were the prime movers wherever large amounts of power were required. Their counterparts in transportation were the puffing wood- and coal-burning locomotives which were competing with mule-drawn canal boats. Domestic transportation was provided by horsecars and carriages jangling leisurely through the streets of the larger cities. Cooking and home heating were dependent on wood and coal stoves. Lighting depended on kerosene and flickering gas lamps. And muscle power of men and horses was the order of the day in performing agricultural, industrial, and household tasks. Such was life as the two small, unobtrusive dynamos, purring quietly in their corner of the Exposition, marked the dawn of the electrical era.

It seems almost unbelievable that electrical energy should be harnessed for so many of our daily tasks in the relatively few years that have passed. Today there are 500 watts of installed generating capacity for every American citizen. Over 40 million homes are wired from central station to wall outlet for use of the power. Every city in the land is lighted electrically. Most any service in communication, entertainment, and transportation, in textile, food, consumer and capital goods industries, and in the home is aided or performed by electrical energy. Electricity has become "the genie in Aladdin's lamp" to save work and provide conveniences.

In this chapter are covered the electrical and magnetic properties of metals that have been put to work in electrical equipment of all

kinds. The subject has been divided into four parts for convenience in discussion. They are:

(1) Resistors and conductors.
(2) Electrical contacts.
(3) Magnetism and electromagnet materials.
(4) Permanent magnets.

Resistors and Conductors *

6.2   RESISTANCE, CONDUCTORS, AND RESISTORS

The rather loose bond between electrons in the outer shell of metal atoms permits electrons to leave one atom and to combine with another. A continuous interchange of electrons between atoms normally occurs, the electrons moving in random directions and at velocities that increase with temperature. The application of an electromotive force between two points in the metal tends to change the random motion of the electrons to a drift from one point toward the other. By convention the electrons flow toward the point of higher or positive potential. The amount of electron flow depends on the potential difference and upon the opposition exerted by the metal. Materials in which an electromotive force causes appreciable drift of electrons, called *current*, are termed *conductors*. All metals are considered conductors but there is a wide range in their opposition to current. Those such as silver, copper, and aluminum, which have low opposition, are said to have low resistance. They are good conductors. Metals such as iron, alloys of nickel, iron, and chromium, and carbon products have higher resistance. They are poor conductors and often they are used as *resistors*.

A few substances containing metallic elements have considerably less electrical conductivity and are known as *semiconductors*. Some commonly used semiconductors are:

	Semiconductor	Used in
Elements	Silicon	Diode rectifiers (radar)
	Germanium	Diodes, transistors
	Selenium	Power rectifiers, photocells
Compounds	Barium oxide	Cathodes
	Lead sulfide	Photocells
	Cadmium sulfide	Photocells, phosphors
	Zinc sulfide	Phosphors

* Prepared from a previous chapter by R. E. Coleman, Jr.

One of the most valuable and useful properties of semiconductors is that their conductivity is not constant but can be changed in various ways. For example, when a semiconductor is heated, it becomes a better conductor and, under appropriate circumstances, the change in resistance may be very sensitive to the temperature. In this way semiconductors can be used to measure or to control temperature. As a second example the conductance of semiconductors may be increased by the absorption of light. With a suitable choice of semiconductor, the change in resistance with light absorption may be very large. This is the basis for application in photoconductive light cells.

Semiconductors contain a few free electrons to give them conductivity intermediate between metals and insulators. But the occurrence of electrons in semiconductors is largely accidental. In metals, the electrons constitute an essential part of the structure, and any given metal always has the same number per unit volume. In semiconductors, most of the electrons come from impurities that have been left in the semiconductor from its method of preparation. The purer a semiconductor can be made, the fewer electrons it contains and the weaker is its conduction. It is calculated that some semiconductors, of which silicon is an example, would be rather good insulators if they were perfectly pure.

Another consideration of equal significance is the ease with which an electron can be moved through the substance. This is called the *mobility*. The mobility is said to be large when the electrons can be moved easily. Relatively speaking, the mobilities in metals are not high and their high conductivity arises primarily from the large numbers of free electrons. For many purposes in semiconductors, it is desirable to have high mobilities Mobilities and available numbers are studied separately in the following way. First a simple measurement of conductivity gives the product, number of electrons times mobility. Second, when a current flows in a substance placed in a magnetic field, a transverse voltage is generated because the moving electrons are pushed aside by the magnetic field (Hall effect). This effect depends only on the number of electrons and not on their mobility. From the two measurements, the number of electrons and the mobility are obtained separately.

Closely connected with semiconductors is another class of substances called *phosphors*. Phosphors are semiconductors that have the special property of producing light. A familiar application of

phosphors is their use in fluorescent lamps and television picture tubes. In each case the source of light is a phosphor. The characteristics of phosphors are determined by the impurities that they contain. In fact, the light actually comes from certain impurities known as "activators" in the phosphor. If the phosphorescent material is sufficiently purified, it loses its luminescent ability.

Before light can be generated, the phosphor must be properly stimulated, or excited. In fluorescent lamps this is accomplished by allowing invisible ultraviolet light to fall on the phosphor. In television tubes, the picture screen, which is composed of a phosphor, is excited by a stream of fast-moving electrons.

Resistivity. No conductors are perfect. They cannot carry electric currents without losses. The power lost during the flow of current is proportional to the square of the current. The coefficient of proportionality is called the *resistance* and is denoted by R, as in Eq. 6.1.

$$W = I^2R \qquad (6.1)$$

in which W = average rate at which electrical energy flowing through the conductor is converted into heat, in watts, I = current flowing in the conductor, in amperes, R = resistance of the conductor, in ohms.

The total resistance, R, of a conductor depends on its length, cross-sectional area, and *volume resistivity*. The latter is a property describing the specific opposition of the conducting material to electron flow. The relation between these quantities is expressed by Eq. 6.2.

$$R = \rho l / A \qquad (6.2)$$

in which:

Symbol		*Units*	
R = resistance of the conductor		ohms	ohms
ρ = volume resistivity of the conducting material		ohm-in.*	ohms/cmf †
l = length of the conductor		in. –	ft
A = cross-sectional area of the conductor		sq in.	cir mil

* Ohm-in. refers to the ohms resistance of a 1-sq-in. section per in. of length (see Eq. 6.2). Thus, it is the resistance in ohms of a cu in. of material. Ohm-cm similarly applies to ohms per cu cm.

† A circular mil (denoted by cir mil or cm) is a term commonly used in electrical engineering to define cross-sectional areas of conductors. It is the area of a circle 1 mil (or 0.001 in.) in diam. Such a circle has an area of 0.7854 × (0.001)² or 0.0000007854 sq in. Thus, a wire 10 mils in diam has a cross-sectional area of 0.7854 × (0.010)² or 0.00007854 sq in., which corresponds to 100 cir mils. Multiply sq in. by 1,273,200 to convert to cir mils. The abbreviation cmf here indicates a

The volume resistivities of the common conducting materials, both in ohm-in. and ohms per cir mil ft, at 68 F (20 C) are given in Table 6.1. The materials are listed in the order of their conductivity, which

Table 6.1   Resistivities of Materials

Material	Composition	Resistivity at 68 F Microhm-in.*	Ohms/cmf	Cond., %	Temperature Coefficient of Resistance,† °F⁻¹
Silver		0.64	9.77	106	0 0021
Copper		0.68	10.37	100	0 0022
Gold		0.96	14 60	71	0.0019
Aluminum		1.12	17.01	61	0 0022
Magnesium		1 81	27.6	37.5	0 0044
Tungsten		2.17	33.1	31	0 0026
Zinc		2.26	34 5	30	0.0021
Cartridge brass	70 Cu, 30 Zn	2.47	37 6	27.5	0.0011
Zamak No. 3	95 9 Zn, 4 Al, 0.1 Cu	2.52	38 4	27	
Nickel		3.08	47	22	0 0030
Phosphor bronze	95 Cu, 5 Sn	3.70	56 5	18	0.0022
Iron		3.93	58.8	17 5	0.0036
Platinum		3.93	58.8	17.5	0.0017
Tin		4.53	69	15	0.0023
Mild steel	99.75 Fe, 0 25 C	4 72	72	14.5	0.0024
Aluminum bronze	90 Cu, 10 Al	5.0	77	13 5	
Magnesium alloy	89.9 Mg, 10 Al, 0.1 Mn	5 1-6 7	80-100	10-13	.
Lead		8 6	132	7.8	0 0021
Silicon bronze	96 Cu, 3 Si, 1 Mn	10.2	155	6.7	
Monel	65-70 Ni, 26-30 Cu, 3 Fe, 1.5 Mn	17.6	268	3.9	0.0011
K-Monel	Monel with 3 75 Al	27.5	420	2.5	..
Stainless steel	18 Cr, 8 Ni, 0.10 C, balance Fe	33.1	500	2.0	
Mercury		37.7	575	1 8	0 00049
Nichrome V	80 Ni, 20 Cr	42 7	650	1.6	0 000072
Nichrome	60 Ni, 15 Cr, 25 Fe	44.3	675	1.5	0.000095
Graphite	(Crystalline)	315	4,800	0.2	.
Carbon	(Amorphous)	1380	21,000	0.05	..

* Multiply resistivity in ohm-in. by 2.54 to obtain resistivity in ohm-cm.
† Multiply coefficient in °F⁻¹ by 1.80 to obtain coefficient in °C⁻¹.

is the reciprocal of resistivity. The conductivity of each material is also expressed as a percentage of the conductivity of copper.

The volume resistivity for most materials changes with temperature. The resistivity at 68 F is generally used, however, to calculate the resistance of conductors. The calculated resistance can then be corrected for other temperatures by using the temperature coefficient of resistance at 68 F, which is denoted by α in Eq. 6.3.

$$R_t = R[1 + \alpha(t - 68)] \qquad (6.3)$$

in which R_t = resistance of the conductor at temperature t, in ohms, R = resistance of the conductor at 68 F, in ohms, α = temperature coefficient of resistance at 68 F, per °F.

Example. A short example will illustrate the importance of resistance and resistivity. Consider a 5000 watt annealing furnace heater located 250 ft away from a 120-volt DC source of electrical power (see Fig. 6.1). Tests show that
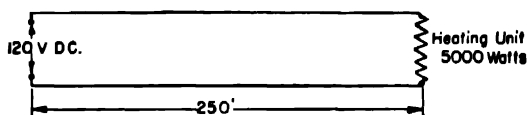

Fɪɢ. 6.1.   Heating-unit circuit.

the heater elements must be operated at 1800 F for this particular application.

Assuming that the allowable transmission loss may be 8 per cent, i.e., 400 watts, then 5400 watts must be supplied by the 120-volt source. The required current equals the power divided by the voltage, 5400/120, or 45 amp. A conductor must have a very low resistance (and low resistivity, also, so that the area and weight may be held within practical limits) to carry 45 amp for 250 ft and waste only 400 watts as heating loss. The required resistance, according to Eq. 6.1, equals the power loss divided by the square of the current, $R = W/I^2 = 400/(45)^2$ or 0.1975 ohm.

The conductor should be of a good conducting material such as copper which has a resistivity of 10.37 ohms per cmf at 68 F. No temperature correction will be used for the conductor because its temperature varies over only a small range and changes more with the seasons than with service.

Equation 6.2 is used to determine the cross-sectional area of a copper conductor for the transmission line. The known values are:

$$\rho = 10.37 \text{ ohms per cmf,}$$

$$l = 500 \text{ ft, total length of conductor,}$$

$$R = 0.1975 \text{ ohm.}$$

Substituting in Eq. 6.2 and solving for A:

$$A = \rho l/R = 10.37 \times 500/0.1975 = 26{,}300 \text{ cir mils, area}$$

The diameter, d, of the wire in mils equals the square root of the area in cir mils. Hence $d = \sqrt{A} = \sqrt{26{,}300} = 162$ mils, or 0.162 in. A diameter of 162 mils or an area of 26,300 cir mils corresponds to AWG No. 6 for the size of the copper conductor (see Table 6.2).

The heating unit must be designed to have a relatively high resistance, for it must dissipate 5000 watts, whereas the 500 ft of No. 6 copper wire dissipates only 400 watts. Copper wire of smaller diameter might be suggested, but the wire would have a very small area, for practical lengths, and it could not withstand the high temperature.

Table 6.2   Standard Annealed Copper Conductors and Their Resistance *

Size, AWG No.	Area, cir mils	Diameter, mils	Lb/1000 Ft	Ohms/ 1000 Ft	Breaking † Strength, lb
0000	211,600	460	640.5	0.04998	5980
000	167,800	409.6	507.9	0.06302	4750
00	133,100	364.8	402.8	0.07947	3760
0	105,500	324.9	319.5	0.1002	2980
1	83,690	289.3	253.3	0.1264	2430
2	66,370	257.6	200.9	0.1593	1930
3	52,640	229.4	159.3	0.2009	1530
4	41,740	204.3	126.4	0.2533	1210
5	33,100	181.9	100.2	0.3195	962
6	26,250	162	79.46	0.4028	762
7	20,820	144.3	63.02	0.508	605
8	16,510	128.5	49.98	0.6405	480
9	13,090	114.4	39.63	0.8077	380
10	10,380	101.9	31.43	1.018	314
11	8,234	90.74	24.92	1.284	249
12	6,530	80.81	19.77	1.619	197
13	5,178	71.96	15.68	2.042	156
14	4,107	64.08	12.43	2.575	124
15	3,257	57.07	9.858	3.247	98
16	2,583	50.82	7.818	4.094	78
17	2,048	45.26	6.2	5.163	62
18	1,624	40.3	4.917	6.51	49
19	1,288	35.89	3.899	8.21	
20	1,022	31.96	3.092	10.35	
21	810.1	28.46	2.452	13.05	
22	642.4	25.35	1.945	16.46	
23	509.5	22.57	1.542	20.76	
24	404	20.1	1.223	26.17	
25	320.4	17.9	0.9699	33	
26	254.1	15.94	0.7692	41.62	
27	201.5	14.2	0.61	52.48	
28	159.8	12.64	0.4837	66.17	
29	126.7	11.26	0.3836	83.44	
30	100.5	10.03	0.3042	105.2	
31	79.7	8.928	0.2413	132.7	
32	63.21	7.95	0.1913	167.3	
33	50.13	7.08	0.1517	211	
34	39.75	6.305	0.1203	266	
35	31.52	5.615	0.09542	335.5	
36	25	5	0.07568	423	
37	19.83	4.453	0.06001	533.4	
38	15.72	3.965	0.04759	672.6	
39	12.47	3.531	0.03774	848.1	
40	9.89	3.145	0.02993	1069	
41	7.84	2.8	0.02374	1349	
42	6.22	2.494	0.01883	1701	
43	4.93	2.221	0.01493	2144	
44	3.91	1.978	0.01184	2704	

* At 25 C for round, bare, solid wire based on National Bureau of Standards. Stranding adds approximately 15 per cent to diameter of equivalent solid wire.
  † ASTM-B3-41.

High-resistance alloys, such as Nichrome, are also suggested since they are used commercially in heating devices operating at 1800 F. They have a high resistivity which permits use of reasonable cross-sectional areas with short lengths to obtain relatively high resistances.

The resistance of the heating unit at 1800 F is calculated by Eq. 6.1, $R = W/I^2 = 5000/(45)^2 = 2.47$ ohms. The value of the resistance at 68 F as determined by Eq. 6.3 is $R_t = R[1 + a(t - 68)]$. If Nichrome is chosen for the heater ($a = 0.000085$ for Nichrome to 1800 F), $2.47 = R[1 + 0.000085(1800 - 68)]$ and $R = 2.47/1.147 = 2.15$ ohms at 68 F.

Tests indicate that a temperature of 1800 F can be attained by passing 45 amp through a coil of No. 12 Nichrome wire that has been close wound on a 0.190-in. diam arbor, and is then stretched to twice its close-wound length.

The length of No. 12 Nichrome wire required to have 2.15 ohms resistance at 68 F can be calculated by Eq. 6.2. Now $R = 2.15$ ohms, $\rho = 675$ ohms per cmf, and $A = 6560$ cir mils, hence $l = 21$ ft. When coiled as noted before, the complete Nichrome heater will be a little over 5 ft long and will have 400 turns.

This example shows that a material with low resistivity (good conductor), copper in this case, is used to *transmit* electrical power with low losses. It also shows that a heating element should be made from a high resistivity material (poor conductor), Nichrome in this case, to *dissipate* the required power with a short length of reasonably heavy conductor.

Superconductivity.   Equation 6.3 holds for temperatures below 68 F, and the R_t for such cases is less than R for room temperature. But at very low temperatures some metals acquire zero electrical resistance (and zero magnetic induction). This property is referred to as "superconductivity." The characteristic temperature at which a metal becomes superconductive depends on the strength of the magnetic field (see Sec. 6.14) surrounding the material and upon whether the field is applied externally or is the result of current used to measure the resistance. Some twenty elements, many alloys, and even compounds of nonsuperconducting elements become superconducting at temperatures ranging from 0.35 K to 16.5 K. Superconductivity is known to be sensitive to structure but its mechanism is still the subject of research.

6.3   SKIN EFFECT

Direct currents distribute themselves uniformly over the cross section of the conductor and therefore use the center of the conductor just as effectively as they use the periphery. Alternating currents, however, owing to inductance effects within the conductor, crowd toward the outside of the conductor. This behavior is known as *skin effect*. It raises the apparent resistance of the conductor, because power loss varies as the square of the current, and the higher density of current flowing near the skin of the conductor produces more power

loss than the lower density of current flowing through the center of the conductor saves.

The values of resistivity given in Table 6.1 are used to calculate the direct-current resistance. The resistivity of the conducting material is unchanged by skin effect; only the total resistance of the conductor increases as the frequency of the current and the diameter of the conductor increase. This increase in resistance should not be neglected in very large conductors at commercial power frequencies and in most conductors at carrier and radio frequencies.

Since skin effect reduces the amount of current carried by the center portion of the conductor, hollow conductors are sometimes employed to use the material more effectively. Aluminum cable steel reinforced (ACSR) is used even more often than hollow conductors. This cable has a steel core which strengthens the cable, and an outer covering of aluminum which, because of skin effect and the high resistivity of the steel, carries most of the current. These conductors also have the advantage of a larger surface area available for cooling.

6.4 PROXIMITY EFFECT

When conductors carrying alternating currents are run very close together, i.e., in a multiconductor cable or a conduit, a phenomenon similar to skin effect occurs; the current distribution in each conductor is disturbed by the currents in the adjacent conductors. This phenomenon is known as *proximity effect* and is often more important than skin effect in increasing the apparent resistance of each conductor.

6.5 COMMON ALLOYS FOR ELECTRICAL-RESISTANCE APPLICATIONS

Electrical-resistance applications include the use of open and "buried" wire, wire coils, wire spools, ribbon, strip, and castings. There are many alloys in use, depending on the resistance needed, the atmosphere involved, the load to be dissipated, and the resistance accuracy to be maintained with temperature variations. Some of the more common alloys and their typical applications are reviewed in the following paragraphs. Their properties are listed in Table 6.3.

The nickel-chromium alloys are the most familiar and probably the most used. Of these alloys the 80 per cent nickel, 20 per cent chromium alloy has the highest oxidation resistance, lowest temperature coefficient of resistivity, high electrical resistance, and retains its strength well at high temperatures. It is used for heating elements

Table 6.3 Typical Properties of Some Common Resistor Materials

Composition	Trade Names	Resistivity,* microhm-cm at 20 C	Coefficient of Resistance,†/°C	Resists Oxidation to °F
80 Ni, 20 Cr	Nichrome V Trophet A Jelliff A Chromel A Alray A	108	2.19×10^{-4} (20–100 C) 0 (800–2000 F)	2100
60–65 Ni 14–16 Cr 20–26 Fe	Nichrome Trophet C Chromel C Alray C	112	1.7×10^{-4} (20–100 C)	1830
40–45 Fe 30–35 Ni 15–20 Cr	Trophet D Chromax	100	3.1×10^{-4}	1400
65 Fe 30 Ni 5 Cr	Chromel D Comet Chromin D	95	8.8×10^{-4}	1300
80 Fe 15 Cr 5 Al	Radiohm Ohmaloy	130	3.5×10^{-4}	2100+
70 Ni 30 Cu	Monel Jelliff 70 Lucero	48.2	10×10^{-4} (20–100 C)	1100
55 Cu 45 Ni	Constantan Advance Copel Cupron Excelsior	49	$\pm0.2 \times 10^{-4}$ (20–100 C)	950
70 Ni 30 Fe	Hytemco	20 annealed 23 hard	45×10^{-4} (20–500 C)	..
87 Cu 13 Mn	Manganin	48.2	$\pm0.15 \times 10^{-4}$	(Must be protected)
86 Cu 10 Mn 4 Ni		30	0.4×10^{-4}	..
Mo		5.5	22×10^{-4} (20–100 C)	1300
Pt		12	21×10^{-4} (20–100 C)	3190

* Values are generalized for each group and differ for specific compositions and manufacturer's products.

† 20 to 500 C, unless otherwise noted.

in industrial furnaces, appliances, and radiant-type heaters, and for voltmeter resistors.

Successively lower oxidation resistance and lower cost is obtained by addition of iron to the nickel-chromium alloys. The highest electrical resistivity is obtained with alloys having 60–65 per cent Ni,

14–16 per cent Cr, and 20–26 per cent Fe. They are used for heating elements in a variety of appliances and for high-resistance rheostats for potentiometers. Alloys with 45–55 per cent Fe, 30–35 per cent Ni, and 15–20 per cent Cr have the highest coefficient of resistivity and are substituted in low priced appliances and heavy-duty rheostats at temperatures up to 1400 F. An alloy which has 30 per cent Ni, 5 per cent Cr, and 65 per cent Fe has still lower cost and is used for car heaters and heavy rheostats. It will rust in presence of moisture.

Aluminum additions to the iron-chromium alloys raise the resistivity, have good oxidation resistance, and result in a high melting point alloy suited to over 2000 F if low creep strength and room temperature brittleness which occurs after exposure at 1400 F are not factors. The 5 per cent Al, 15 per cent Cr and balance Fe alloy is used for radio resistance applications. Another alloy of this type, known as Alchrome, Alcres, Ohmax, and Magapyr, has about 20 per cent Cr and 5 per cent Al balance iron. Smith number 10 alloy with 7½ per cent Al, 37½ per cent Cr has a resistivity of 167 microhm-cm. The latter grades are often used for electrical furnaces.

Another series of resistance alloys is the iron-chromium-aluminum system with small additions of cobalt. One of these having about 25 per cent Cr, 5 per cent Al, 3 per cent Co and balance almost pure iron is marketed as Kanthal. It has a resistivity of 135–145 microhm-cm at 20 C and 15 per cent less density than the nickel-chromium alloy. It is used for compact electric-heating units suited to sulfurous atmospheres and temperatures above 2000 F, but the alloys are brittle when cold and have low tensile strength at elevated temperatures.

Nickel and copper form a series of alloys that are of importance to electrical-resistance applications. Starting with alloys rich in nickel, such as Monel (70 per cent Ni, 30 per cent Cu), successively lower resistance is obtained as the proportion of copper is increased. The 55 per cent Cu, 45 per cent Ni alloy has practically zero coefficient of resistivity, relatively high resistance, and high electromotive force with copper. It is used for precision-instrument rheostats, voltmeter resistors, and low-temperature control resistance elements. The resistivity of the lower nickel-content alloys graduate from 30 microhm-cm for 23 per cent nickel to 5 microhm-cm at 2.25 per cent nickel and are used for relay coils and radio resistors of specific resistance.

An alloy of 70 per cent Ni and 30 per cent iron is of importance because it has a high temperature coefficient of resistance equal to pure nickel but about twice the specific resistance. It is suited to self-regulating applications such as immersion heaters and heating pads. Carbon resistors also have high positive temperature coefficients.

An alloy especially suited to low-voltage d-c applications is 86 per cent Cu, 10 per cent Mn, 4 per cent Ni. It has a high resistivity and a very small thermal electromotive force against copper. The temperature coefficient of resistance is low over the room temperature range and the resistance is maximum at 25 C. Thus, the material is well suited to slide-wire bridges, shunts, and potentiometers of electrical instruments which must be of high precision and stable with small temperature variations. An alloy of 87 per cent Cu and 13 per cent Mn has a similar temperature coefficient of resistance but is subject to selective oxidation and must be aged at 120 C for 24 hours to eliminate slow decrease in resistance with time. Some of the silver-base manganese-tin alloys also have a temperature coefficient of resistivity which approaches zero at temperatures between 0 and 200 C. Nickel alloys with 4–5 per cent Mn having high resistivity and a high temperature coefficient are used for radio tubes and grid wire.

The 10 per cent Mn and 10 per cent Sn silver alloy has a negative coefficient which is desirable for compensating purposes. Mixtures of Fe, Ni, and Co oxides (*Thermistors* and *Electrotherms*) have a very high negative coefficient and are also suited for compensation purposes as well as for detection.

For temperatures well above the limit for nickel-chromium alloys, molybdenum, platinum, and 10–20 per cent rhodium-platinum alloys are used. The molybdenum must be coated with beryllium oxide and a special refractory outer coating for operation in air.

ELECTRICAL CONTACTS

by B. W. JONES *

In practically all types of current-carrying apparatus and controls it is necessary to provide means for closing and opening electrical circuits. These "making" and "breaking" functions are performed

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by bringing together and separating two contact materials. Millions of devices are manufactured each year which depend upon the successful performance of many types of contacts. A whole power system, for example, relies on successful current interruption for protection, and many human lives similarly depend on contacts to bring aircraft landing gear and other elements into operation. The study of contact materials is therefore worthy of engineering attention.

To the casual observer the reactions that transpire in contact operation may seem of little importance or interest. But a study of these reactions reveals some of the most interesting and puzzling chemical and physical phenomena. Relatively little is known and understood of the fundamental considerations involved. But correlation of field experience with laboratory tests has indicated a number of characteristics that are important to successful contact operation. These are briefly reviewed in the following paragraphs.

6.6 CONDITIONS UNDER WHICH CONTACTS MUST FUNCTION

Contacts must function under extreme ranges of conditions. The pressures that hold contacts together range from fractions of a gram to thousands of pounds. The currents correspondingly range from milliamps to kiloamps, and the applied voltages have a similar range. The contacts may have to make, break, and carry these currents, or they may have to do only one or two of these things. Also, the contacts may have to operate in air, in oil, or in some other medium. These operating conditions tend to cause: (1) welding or sticking of the contacts, (2) overheating from several causes, or (3) short life as a result of arcing. But by the selection of the most suitable contact materials, these objectionable tendencies may be either eliminated or minimized.

6.7 CONTACT RESISTANCE

When two clean contacts are brought together and held with a specified pressure, they may be touching in one or in several minute spots, each of which will be only a few sq mils in area. The number of spots increases with the pressure, since a static balance is created between the pressure and the yield point of the contact material. This means that the *contact resistance is a restrictive resistance* through these small contact spots (see Fig. 6.2). Its value is determined by a combination of: (1) the specific resistance of the contact material, (2) the contact film or interface film that may be on the

surface of the contact, and (3) the fact that current may not flow through the entire spot areas which are in physical contact.

The above static balance on the load-bearing surface will be modified if current starts to flow through these minute spots.   The current
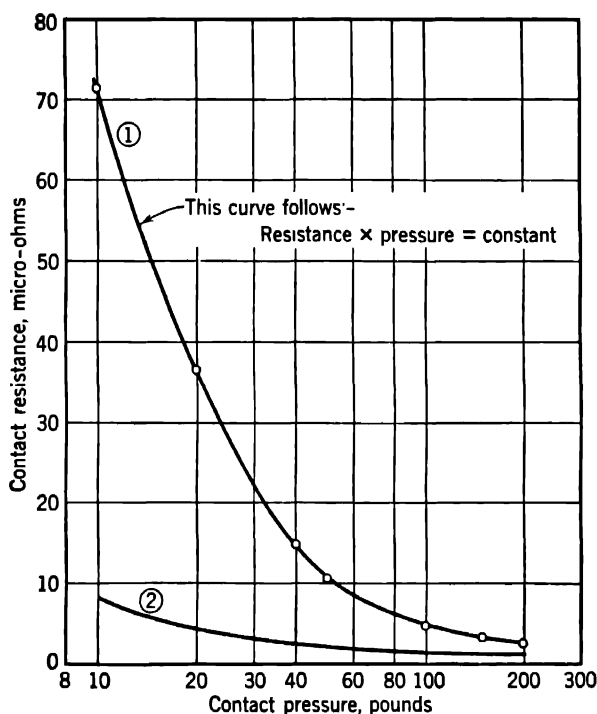
FIG. 6.2.   Resistance versus pressure for a pair of copper contacts.   Curve 1 is for 1 in. x 1 in. flat dry contacts   Curve 2 is for 1 in. width 3 in. radius of curvature contacts with vaseline on the surface.

density in the restrictions may reach many thousands or even millions of amp per sq in.   Local heating is induced that will soften these small cross sections, and therefore the statically balanced sections will require a larger load-bearing surface to remain in balance.   This current effect requires a few minutes to become stable, following a current increase.   If the current is decreased, the resistance will not go back up because the cross section of the spots will not decrease.

The resistance of a clean contact is therefore affected by two factors: pressure and current.

6.8 RESISTANCE CHARACTERISTICS OF SURFACE FILMS ON CONTACT MATERIAL

When an electric contact becomes oxidized or sulfided, which are the most common forms of surface films, its contact resistance increases manyfold. Sometimes actual failure to make (insulation) occurs on 110 or 220 volts. The oxide or sulfide films that form on some metals are much more likely to insulate or to cause trouble than other types, although all films will cause increased contact resistance. The oxides or sulfides that form on aluminum and chromium have extremely high resistance, on copper they are quite bothersome, and on silver they sometimes cause trouble.

If two duplicate contacts, which had previously been oxidized or sulfided, are held together with a given force and their contact resistance measured by the voltmeter-ammeter method (wherein the current is gradually increased over a wide range of current), the contact resistance will decrease approximately as much as the current increases. The reason for this characteristic is that a metal oxide or sulfide has a negative specific-resistance characteristic, whereas the metal itself has the same specific resistance irrespective of the current value. This is illustrated in Fig. 6.3.

Silver has a very unique characteristic as regards its oxides or sulfides and is different from most of the other contact materials. When either silver oxide or sulfide is heated above 200 C or 300 C, it will revert back to pure silver. The minute contact spots described above become much hotter than the average temperature of the contact and, at these operating temperatures, the silver contacts will operate quite normally, although they had previously been oxidized or sulfided. This phenomenon does not obtain for the other common types of contact metals. Therefore, silver is a very commonly used metal because it also has a very low specific resistance and will carry moderate currents indefinitely without seriously overheating.

6.9 THE LIFE OF CONTACTS WHEN ARCED IN AIR

If contacts are required to make and to break frequently an a-c circuit of 100 amp or less in air, it has been observed that the life of the contacts is determined by their tendency to oxidize. Every time an arc occurs at a contact surface, a certain section will be heated to incandescence. During the arcing period the incandescent area will oxidize, or burn, at a rate depending upon its oxidizing characteristic, and it may also vaporize because of the arc temperature. Copper oxidizes very rapidly, but silver oxidizes very slowly; silver, there-
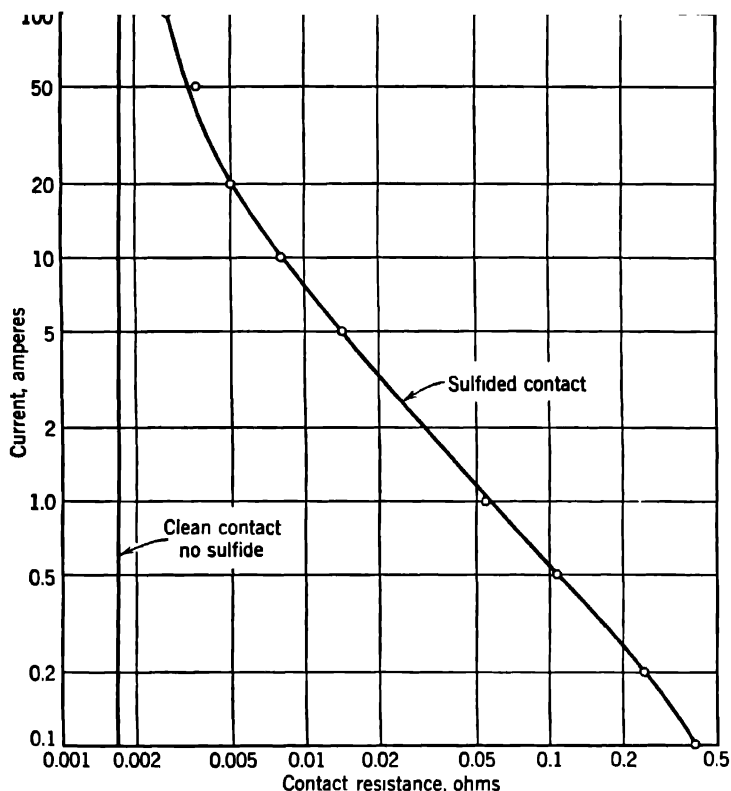
Fɪɢ. 6.3.   Current flow versus contact resistance for sulfided silver mating contacts. Contact pressure was 8 oz, and current was increased from 0.1 to 100 amp. The resistance will remain substantially constant at its highest current value when the current is decreased.

fore, will give a very much longer life than will copper when handling small or medium currents.

If a contact is required to handle very large currents, similar to short-circuit currents, silver does not prove satisfactory. The reason is that contacts must have a large thermal capacity to function satisfactorily on very heavy currents. Silver has a low thermal capacity. By thermal capacity is meant the amount of energy required to melt or to vaporize a given cubical content of the contact. During a heavy current arc there is nothing that can absorb this energy except the thermal capacity of the contact. When the current is light, the surrounding metal can conduct the heat away from the arced spot, and therefore the thermal-capacity factor is not predominant. Tungsten,

molybdenum, nickel, copper, and other materials have more thermal capacity than silver. Mixtures or alloys of these metals are therefore frequently used for heavy arcing. It can be said that for contacts to give good life when handling low or medium currents (100 amp or less), it is essential that the contact material be fairly inert to oxygen; but when handling very high currents (5000 amp and above), then the contact material must have a large thermal capacity. Of course, the relative importance of these two characteristics will cross somewhere between these two current values.

6.10   THE LIFE OF CONTACTS WHEN ARCED IN OIL

When contacts interrupt an arc in oil, the arc generally remains on the same spot of the contact during the entire arcing period. This effect is caused by the viscosity of the oil, which prevents the arc from moving. Under this condition the contact material is not appreciably attacked by oxygen, but the impinging of the arc on the one spot causes localized melting. The degree of melting is a function of the thermal capacity of the material. Silver will therefore give a short life under oil; copper will give about twice the life of silver; and a copper-tungsten mixture will give about twice what copper will give. But all contact materials have less life in oil than in air. The reason why devices are oil immersed is generally to isolate them from corrosive or explosive gases in the surroundings.

As a rough check on the expected life of a copper contact when interrupting a-c power, refer to Fig. 6.4, which indicates the expected life of a pair of copper contacts (two mating contacts) when they were subjected to several values of a-c currents. The life of these contacts corresponded to a material loss of 4 g from the pair. Since the life of a pair of contacts is a direct function of the amount of metal that can be sacrificed before reaching the limit of its wear allowance, the expected life can be estimated by multiplying the value read from Fig. 6.4 by one-fourth the expendable number of grams from a pair of the contacts under consideration.

6.11   ELECTRICAL-CONTACT MATERIALS

Copper, silver, tungsten, cadmium, nickel, carbon, mercury, palladium, and gold are the metals most used for contacts. Of these materials copper, silver, tungsten, and carbon constitute a very large percentage of the whole. Contact characteristics of these 9 elements are briefly reviewed in the following paragraphs.

Copper has all the essential features of an excellent contact material except for its affinity for oxygen.   It is inexpensive, has a low specific resistance, is ductile, has a medium melting and boiling point, and has a fairly high thermal capacity.   However, it has a voracious appetite for oxygen, which causes a very high resistance film to form over the surface.   This copper oxide—and also copper sulfides— frequently causes copper contacts to overheat, and sometimes causes
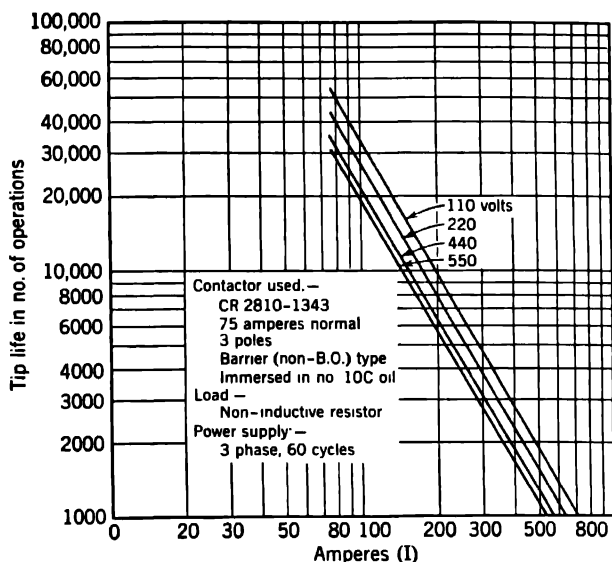
Fɪɢ. 6.4.   Life in number of operations for removal of 4 g from oil-immersed mating copper contacts versus amp at several voltages.

them to become insulated on 110 or 220 volts.   The tendency for copper to oxidize, or burn, also results in a short life when it is required to make and to break a current.

Silver has many excellent characteristics as a contact material, but it has one or two that are not so good.   It costs approximately 20 times more than does copper, and its thermal capacity is low, making it unsuitable as an arcing contact on high currents.   Also, it is not entirely satisfactory for very low contact pressures—less than 1 oz— because it will occasionally insulate on 110 volts.   With the exception of these limitations, silver is an outstanding contact material and is now being used extensively.

Tungsten has some very unusual characteristics and can do certain kinds of contact work very nicely, but these applications are quite restricted.   Tungsten is generally used for ignition contacts, provided

the current does not exceed about 10 amp. Silver and tungsten contacts make a good mating pair for very frequent operation on small d-c power circuits where the silver contact is the anode and the tungsten contact is the cathode. This arrangement prevents a build-up on the cathode caused by metal transfer. Tungsten is used in many ways, but these two applications illustrate its typical uses.

Cadmium is adjacent to silver in the periodic table and therefore similar to silver in many ways. But it has a very low melting point, which makes it very easy to weld or to disintegrate rapidly when arced. It is therefore not commonly used by itself as a contact, but is frequently used to form alloys.

Nickel, like cadmium, is also not commonly used as a complete contact but is frequently used as an alloy. A mixture of 85 Ag-15 Ni has some very good characteristics for "life" and "current-carrying" abilities.

Carbon has many handicaps, such as its brittleness, its very high specific resistance, and the difficulty of attaching it to metal supports. It does have two characteristics that make it attractive for some applications. One of these is that it is not attacked by oxygen at low temperatures, nor by sulfur, so that it has a high surety of making a circuit on light pressures. The second desirable characteristic is that carbon will not weld.

Mercury is the only element used for contact purposes that is a liquid at ordinary temperatures. Because of this characteristic it is sometimes used as a contact for making, breaking, and carrying current, such as in vacuum or gas-filled tubes or enclosures. Its tendency to amalgamate and to oxidize makes it very tricky unless careful precautions are used.

Palladium is one of the rare and expensive elements but it has one characteristic that makes it attractive for certain applications. It is attacked but very slightly by oxygen or by sulfur, and therefore it can be used for contacts that have very light pressures (less than an oz) and where the current to be handled is small (a fraction of an amp). As an example, it is used for small telephone relays in communication circuits, where surety of making a circuit with light pressures and with a low voltage is essential.

Gold, like palladium, is one of the rare and expensive elements. It also can be used where the pressures and the voltages are low and the current is small. But gold is very soft and welds very easily. It is used less often than some of the other rare noble metals and alloys.

5. *Life.*   Contact life is determined by the weight loss of material which will cause malfunctioning.   Rate of oxidation is the determining factor for low and medium currents in air.   The life of a pair of fine silver contacts in air at less than 300 volts, on 60 cycles, at 100 amp or less, is given approximately by Eq. 6.4.

$$N = \left(\frac{30}{I}\right)^2 V \tag{6.4}$$

N = number of makes and breaks; I = current to be made and broken; and V = useful volume of contact in cubic mils (70 or 80 per cent of actual volume of silver in smallest contact).

The silver alloys 99 Ag-1 Hg, 85 Ag-15 Ni, and 99 Ag-1 Pd rate about as well as silver at 50 amp and 550 volts and below.   Less life is obtained in oil.   For very high currents, high thermal-capacity contact materials are far superior to fine silver.

6. *Contact Material Transfer.*   When a d-c circuit is made and interrupted by two contacts in air, material is generally lost from the anode (positive terminal) and gained by the cathode.   A small sharp cone frequently builds up on the cathode with currents of 1 amp or less, with a corresponding pit in the anode.   A larger mound often accompanies currents of 10 to 100 amp.   Dissimilar contact materials generally reduce this transfer.   A low-resistance contact material such as silver is recommended for the anode, and a high-resistance material such as tungsten for the cathode.

MAGNETISM AND ELECTROMAGNET MATERIALS

by L. T. RADER *

6.13   THE NATURE OF MAGNETISM

All substances can be divided into one of three classes—paramagnetic, diamagnetic, and ferromagnetic—depending on how they react when subjected to a magnetic field.   Paramagnetic substances are those that are only feebly magnetic.   Diamagnetic substances actually set up fields that oppose applied fields.   Ferromagnetic substances are very strongly magnetic and are the substances of greatest practical interest as magnetic materials.   They include iron, nickel, cobalt, and some alloys.

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The present-day theory of ferromagnetism attributes the magnetic properties of a substance to electron spin. The electron is thought to be spinning about an axis through its own center, in addition to its rotation around the nucleus of the atom. Electron spins and electron charges influence each other by trying to keep the spins parallel in neighboring atoms, whereas the forces of thermal agitation tend to destroy the lineup. The effect of these electron forces is the formation of small regions, about 0.001 in. cube, known as *domains*. Each domain includes about 10^{15} atoms, but the forces are such as to make this grouping act as a single unit. Ferromagnetic substances consist entirely of such domains, each magnetized in a definite direction. In iron, for example, there are six directions, a positive and a negative for each of three Cartesian axes, in which it is relatively easy to magnetize a crystal of the material.

The familiar concept of considering magnetic material to be made up of a large number of elementary magnets, or dipoles, is thus seen to be a reasonable physical picture. A domain is, in effect, such an elementary magnet, whose direction will change when a magnetic field is applied.

6.14 DEFINITIONS

A *magnetic field* is a region in which magnetic forces exist. It is created either by electric currents (in electromagnets) or by permanent magnets. The *field strength* (also called "magnetic intensity" or "magnetic force") *is the force which would be exerted by the field on a unit magnetic pole* * *placed at that point.* A common physical concept pictures the field as being filled with *lines of induction.* The number of lines of induction per sq cm is usually denoted by the letter B with the units of *gausses.* Other terms often used synonymously with lines of induction are *lines of flux, maxwells, lines of flow, normal induction,* or simply *lines,* or *flux.*

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* A unit magnetic pole is defined as a magnet pole of such strength that it will exert a force of one dyne upon an equal pole at a distance of one centimeter, both poles being in air. This is expressed by

$$f = K \frac{m_1 m_2}{r^2}$$

where $K = 1$, if units are dynes and centimeters, and m and r represent pole strength and separation respectively. An isolated unit pole does not actually exist, but it is approximated by a long, needlelike magnet in which the poles are widely separated.

The source of the flux is known as the *magnetizing force* and is denoted by H with units of *oersteds*. (The engineering unit is the amp-turn/in.) Since most magnetic material is used in electromagnets, the ASTM defines H by the equation

$$H = 0.4\pi nI \qquad (6.5)$$

where H is the magnetizing force is oersteds at the center of a long solenoid,* of such length that the end effects are negligible, of n turns per cm, and carrying a current of I amp (see Fig. 6.5a). This is also the same as the magnetizing force at the mean diameter of a uniformly wound ring or toroidal solenoid (Fig. 6.5b). The ring solenoid or closed circuit is ordinarily used in testing magnetic materials, and the magnetization data are usually presented by plotting a graph with B in gausses, or in lines per sq in., vs. H in oersteds, or in ampturns/in., i.e., flux density vs. magnetizing force (see Fig. 6.6). If no ferromagnetic material is present, H and B have the same numerical value at any point, in metric units.

(a) Long Solenoid, $\frac{\ell}{d} \doteq 10$

(b) Toroid

Fig 6.5. (a) A long solenoid, with an air core produces a magnetizing force, $H = 0.4\pi nI$, at its center. (b) A toroid with an air core produces a field of equal strength.

The total magnetizing force in a magnetic circuit is termed the *magnetomotive force*, and is abbreviated mmf.

6.15 MAGNETIZATION

A ferromagnetic specimen is unmagnetized when the domains are oriented at random. In such a situation there is no net mmf across the specimen, and it does not produce any magnetic field outside itself. Thus, B and H are equal to zero.

* A solenoid whose length is equal to or greater than 10 times its diameter is a "long solenoid."

Consider a toroidal solenoid wound on a nonmagnetic core, such as is shown in Fig. 6.5b. If the flux density is measured on the centerline of the toroid, the relationship between B and H is given by the straight line OA in Fig. 6.6. If now the space within the toroid is filled with an unmagnetized ferromagnetic material, the well-known
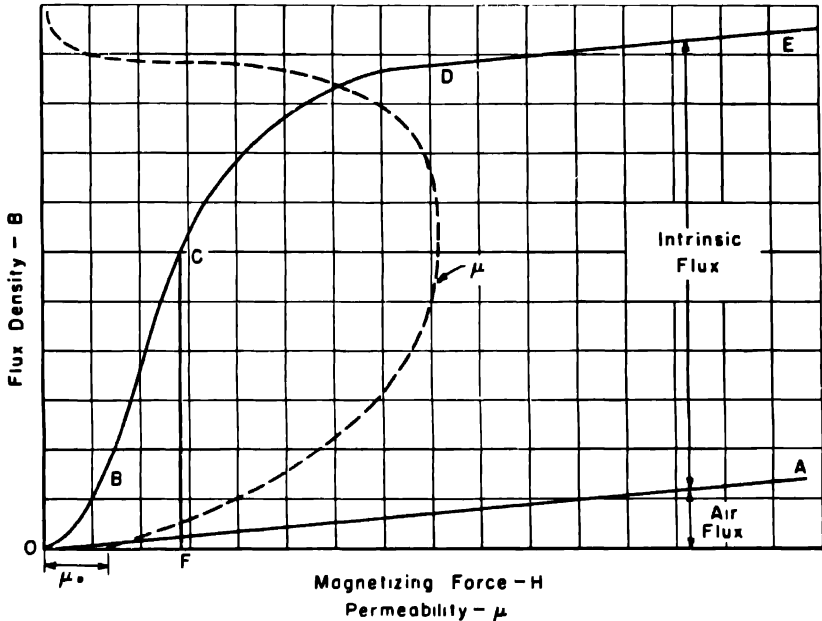
FIG. 6.6. Magnetization curve for a ferromagnetic material. The ratio of CF to OF is the permeability at point C. The dotted line shows the variation of permeability with flux density. The slope of the air-flux line (OA) is exaggerated for clarity.

magnetization curve, OBCDE, is obtained. The magnetization curve has many names, being referred to as the *B-H curve*, the *magnetic saturation curve*, the *virgin curve*, or simply the *saturation curve*.

The increase in flux, B, in ferromagnetic material occurs when the magnetic field acting on the domains orients them in the direction of the field, so that the mmf of each domain, or elementary magnet, is in such a direction as to increase the flux produced by the external field. The straight part of the curve, BC, is traced out because the domains, influenced by a field, easily turn into those directions of magnetization that have a component in the direction of the magnetizing force. As the magnetizing force increases, the domains are

with greater difficulty oriented into the exact direction of the field This gives the rounded part of the curve, *CD*, commonly known as the *knee*. The knee is not usually a very well-defined point, except in certain special materials. As the applied current is further increased,
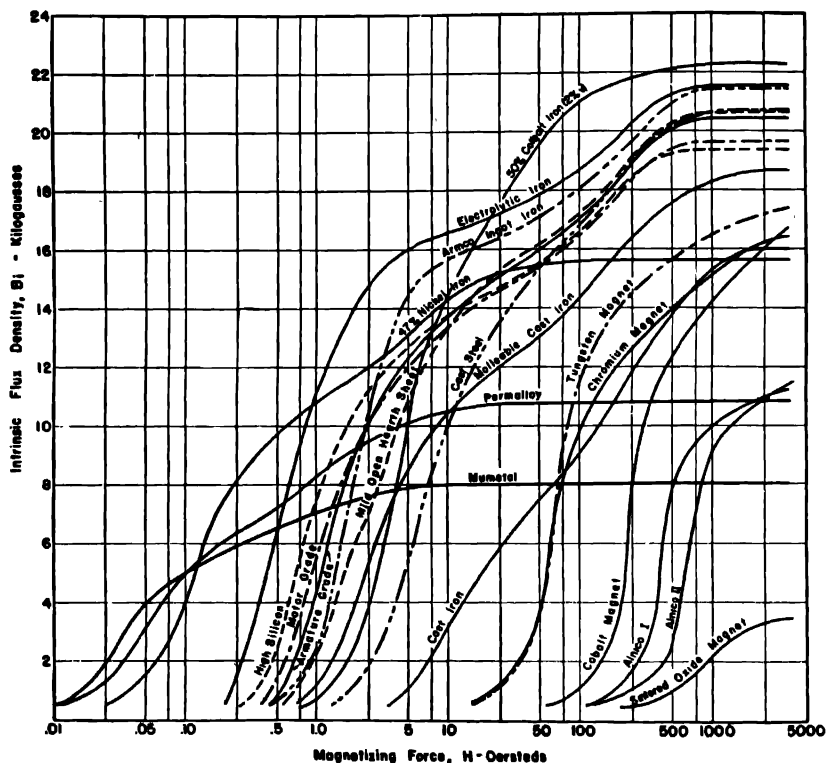
Fɪɢ. 6.7. Magnetization curves for several ferromagnetic materials. Intrinsic flux density is plotted vs. magnetizing force. Note logarithmic scale for the latter.

the magnetization curve ultimately attains the slope *DE*, equal to that of the air line *OA*. The material is then said to be *saturated*.

The difference in flux between the saturation curve and the air line, *OA*, at any magnetizing force, is due to the contribution of the magnetic material. This flux is known as the *intrinsic flux* and gives a truer measure of magnetic properties than does the total flux, especially at very high mmf's. The point at which the intrinsic flux density curve becomes horizontal gives the *intrinsic saturation*.

Many common magnetic materials are compared in Fig. 6.7, which

has H plotted on semilog coordinates as abscissa, and intrinsic flux density, B_i, as ordinate. It provides a basis for dividing materials roughly into three main groups. The first group includes those materials to the extreme left of the curve: nickel-iron alloy (Nicaloi), Permalloy, and Mumetal. These give appreciable flux densities at very low magnetizing forces. The next group may be considered as including the materials between electrolytic iron, on the one hand, and steel or malleable iron castings, on the other. In this group are the bulk of industrial magnetic materials. The third group is at the right-hand section of the curve and consists primarily of the permanent magnet materials.

The cobalt alloys have the highest intrinsic saturation values and are followed in decreasing order by electrolytic iron, Armco iron, cold-rolled steel, low-silicon steel, high-silicon steel, iron-nickel alloy, Permalloy, and Mumetal.

6.16 PERMEABILITY

Referring to Fig. 6.6, the ratio of the ordinate B, at any point, to the abscissa H, where B and H are in metric units, such as CF/OF, is known as the *permeability*, μ. The dotted curve in Fig. 6.6 shows how μ varies with flux density. The actual slope of the B-H curve at any point is called the *differential permeability*.

In terms of this definition, a vacuum, or free space, has a permeability of unity; a diamagnetic material has a permeability less than unity; a paramagnetic material has a permeability slightly greater than a vacuum and approximately independent of the magnetizing force; and a ferromagnetic material has a permeability which is considerably greater than unity and varies with the magnetizing force. The class of metals lying between paramagnetic and ferromagnetic is often called *feebly magnetic*.

If both sides of Eq. 6.5 are multiplied by μ, then

$$\mu H = 0.4\pi n I \mu = \frac{0.4\pi N I \mu}{l} \tag{6 6}$$

where N is the total number of turns and l is the length of the straight solenoid (or the mean circumference of the toroidal solenoid) in centimeters. Since $B = \mu H$, Eq. 6.6 may be written

$$B = 0.4\pi\mu \frac{NI}{l} \tag{6.7}$$

In engineering units Eq. 6.7 can be written as

$$B'' = 3.1\mu \frac{NI}{l''} \tag{6.7a}$$

For a field in air this becomes

$$B'' = 3.1 \frac{NI}{l''} \tag{6.7b}$$

where NI = amp turns causing the magnetic field, B'' = flux density in lines per sq in., l'' = length of air path under winding in in.

The total flux in any area, assuming B is constant over the area, is $\Phi = BA$ where A is the cross-sectional area in sq cm. Therefore

$$\Phi = 0.4\pi NI \frac{\mu A}{l} = \frac{0.4\pi NI}{l/\mu A} \tag{6.8}$$

6.17   ANALOGY WITH ELECTRICAL CIRCUITS

The quantity $l/\mu A$ is known as the *reluctance*, by analogy with the electrical resistance $(\rho l/A)$, so there is, in effect, an Ohm's law for magnetic circuits which states that

$$\text{Flux} = \frac{\text{Total mmf}}{\text{Reluctance}} = \frac{\mathfrak{F}}{\mathfrak{R}} \tag{6.9}$$

Comparing the equations

$$\Phi = \frac{\mathfrak{F}}{\mathfrak{R}} = \frac{\text{mmf}}{l/\mu A} \quad \text{and} \quad I = \frac{E}{R} = \frac{\text{emf}}{\rho l/A} \tag{6.9a}$$

it is evident that

$$B = \frac{\Phi}{A} = \left(\frac{\text{mmf}}{l}\right)\mu \quad \text{and} \quad i = \frac{I}{A} = \left(\frac{\text{emf}}{l}\right)\frac{1}{\rho} \tag{6.10}$$

The term mmf/l is defined as H, and μ is the permeability of the material under magnetization. This permeability determines what flux density will "flow" under the magnetizing force, H. In empty space, μ is unity, and B and H, that is, lines of induction and lines of force, have the same numerical value. In the electrical circuit, $1/\rho$ is the conductivity of the material in the circuit and determines what current density, i, will flow under the voltage gradient E/l. As shown

by Eq. 6.9a the total flux is related to the magnetomotive force and the constants of the magnetic circuit, just as Ohm's law relates the current to the voltage and resistance of a d-c electric circuit. For magnetic circuits it is more practical, partly because of the nonlinear nature of μ, to give data in terms of flux density and amp turns per unit of length.

Using Eq. 6.9 and the law of continuity of flux (all lines of flux are closed loops), magnetic circuits in parallel or in series can be solved in exactly the same manner that d-c electric circuits are worked out.

The analogy between magnetic and electric circuits is not complete, and they differ in several respects. The permeability, μ, varies considerably, whereas the electrical resistivity, ρ, is relatively constant for a conductor. There is also less difference between the permeability of the magnetic path and the permeability of the surrounding medium than there is for the resistivity of the conductor and the surrounding medium. This results in a less well-defined circuit for magnetic flux and leads to the phenomenon of *leakage flux*, which is vitally important in electrical apparatus. Further, the cross-sectional area of magnetic circuits is comparatively large, and large errors can be made by assuming uniform flux distribution.

6.18 HYSTERESIS LOOP

The hysteresis loop is a curve plotted between B and H for various values of H from a maximum value in the positive direction to a maximum value in the negative direction and back again. Fig. 6.8 shows a typical hysteresis loop.

Starting at zero with a coil wound around a toroid of unmagnetized iron, the magnetization curve follows curve OD. If the mmf is gradually reduced, the flux curve follows the line DE. As mmf is reversed, the flux falls to the point L and thence to M. As the mmf is returned to zero, the flux traces out the path MN. Then, as mmf is again increased, curve NPD is followed. The area within the closed loop is a measure of energy lost during the cycle. This energy is, in effect, a frictional loss and shows up as heat in the material. The distance OE is a measure of the residual flux left in the *closed* magnetic circuit when the current is zero. It is known as B_r, the *residual induction*. B_r describes circuits in which there are no air gaps, e.g., the iron toroid, and should not be confused with *remanence,* a more general term which refers to the magnetic induction remaining in the magnetic

circuit (usually in the air gap when one is present) after the magnetizing force has been removed.

The distance OL is known as $-H_c$, the *coercive force,* and is the value of the demagnetizing mmf required to bring the residual or remanent magnetic induction to zero when such a loop is being traced out.

If a ferromagnetic substance is subjected to an alternating mmf, the first hysteresis loops traced out do not necessarily fall upon each other. When successive loops retrace preceding ones, the material is said to be in a *cyclically magnetized* condition. For electromagnet core materials, values of B_r and $-H_c$ are determined from a hysteresis loop taken when the material is cyclically magnetized. Permanent-magnet values, however, are taken from the first hysteresis loop, since permanent magnets need be magnetized only once.

FIG. 6.8. Hysteresis loop for a ferromagnetic material. Curve OD is the magnetization curve; length OE is the residual induction; and length OL is the coercive force. The width of the loop, LP, is much exaggerated, compared with materials used in magnet cores.

6.19 CORE LOSS

The total core loss is the sum of the hysteresis losses and the eddy current losses. It is determined in practice by the *Epstein test,* in which a sample of standard dimensions is operated with a standard flux density and frequency, and the power loss in the sample is measured.

HYSTERESIS LOSS   The hysteresis loss is proportional to the area of the hysteresis loop. Steinmetz developed the law:

$$W_h = \eta f B^x \tag{6.11}$$

where W_h = watts hysteresis loss, per cu cm, η = constant proportional to the area, material, heat treatment, etc., f = frequency, cps, B = maximum flux density attained, gauss, and x = 1.6 for some types of iron.

On many present-day materials, the exponent x is considerably greater than 1.6, being almost equal to 3 for some silicon steels. Hysteresis losses are ordinarily taken at various densities in laboratory tests, since no value of η will fit the loss curve over a wide range of values of density. Misuse of the equation will usually bring about very large errors.

EDDY-CURRENT LOSS Whenever the flux in a magnetic material changes its value, voltages are induced which cause eddy currents to circulate in the material. The value of the eddy-current loss depends on the resistivity and thickness of the material, the frequency, and the flux density as shown by the following equation:

$$W_e = \frac{Kf^2B^2t^2}{\rho} \qquad (6.12)$$

where W_e = watts eddy-current loss per cubic centimeter; $K = 1.645 \times 10^{-16}$; f = frequency in cycles per second; B = maximum flux density in gausses; t = lamination thickness in centimeters; ρ = resistivity in ohm-centimeters.

The eddy-current losses given by the formula are generally lower than actual test values. Data on these losses are therefore obtained from laboratory tests rather than from theoretical calculations.

It has been proved that the eddy-current loss increases with increasing grain size up to the point where the grains become as thick as the laminations. This leads to higher-than-calculated losses for materials such as silicon steel, which have large grain size.

The eddy-current loss is shown by Eq. 6.12 to vary as the square of the thickness of material used. To reduce these losses, magnetic structures for use on alternating current are usually made of thin sheets or laminations insulated from each other. Despite theory, it has also been shown that eddy-current losses are not directly proportional to the square of the lamination thickness but decrease less rapidly than the square law with decreasing thickness. There is a limit in lamination thickness below which it is not feasible to go because of the excessive space taken by the electrical insulation on the sheets. Since this insulation is of approximately the same thickness, independent of sheet thickness, the percentage of nonuseful space increases as the lamination thickness decreases.

6.20 OTHER FACTORS AFFECTING CORE LOSS

Several factors tend to make core losses in electrical apparatus greater than those measured by the Epstein test. The Epstein test must, in fact, be treated primarily as a standard to define purchasing specifications and material identification, and cannot be used for absolute design engineering values. Some of these factors that often make losses in apparatus considerably higher than Epstein tests would indicate are discussed below.

Burrs. As dies became worn, the burrs that they form on punched edges of lamination stock become larger and larger. These burrs are not always removed by deburring operations, and they cut through sheet insulation forming contacts between laminations and allowing excessive eddy currents to flow. These are commonly referred to as intersheet eddy currents. Machining operations that are performed on stacked laminations, such as the grinding of induction motor stators or broaching of solenoid faces, often smear the laminations together, forming good connections between sheets. Many schemes, such as treating the faces with acid or alkali, have been tried in an attempt to eat away the metal particles after laminations have been assembled into apparatus, but this attempted cure often causes other troubles, such as rusting. Burning off the burrs with a flame has also been attempted, with varying success.

Rivets and Bolts. Laminations must be held together. A common method is to use rivets or bolts, but they tend to short circuit lamination insulation. Rivets and bolts very often form part of a closed magnetic loop which, under a-c operation, may cause a serious loss of electrical energy.

Pressure. Mechanical strains set up in magnetic materials, either from (a) cold working during rolling or punching or (b) distortion during final assembly operations, affect magnetic properties in several ways. The hysteresis and eddy-current losses as well as the magnetizing current are increased. The increased hysteresis loss due to punching depends upon the material, its thickness, and the configuration of the grains. The loss may be as high as 300 per cent of the loss in the unpunched sheet. The strains produced by punching operations increase the loss primarily in the narrow section next to the punched edge. The per cent increase in hysteresis loss is much lower for high flux densities than for low ones.

The effect of tension on silicon steel is to increase the permeability until high flux densities are reached. The effect of compression,

however, is much more marked than that of tension and reduces the permeability considerably. Fig. 6.9 shows the effect of compression on the saturation curve of a 3 per cent silicon steel.

Hysteresis Loss in Silicon Steel Scale. The surface scale on iron and steel (usually an oxide) is partially magnetic and at high flux densities it carries appreciable flux.

Since the scale has a very high hysteresis coefficient, as it begins to carry flux the total hysteresis loss increases rapidly. This type of loss is lessened by removing the oxide by acid pickling, and the laminas are then coated with an enamel having an inherently low hysteresis loss.

Aging. The normal or accelerated change in magnetic properties of a magnetic material under normal or specified conditions is called "aging." When used in reference to core loss in an electromagnet material, this term implies an increase in loss. When used in reference to permeability or rema-

Fig. 6.9. Magnetization curves drawn to scale for a 3 per cent silicon sheet steel sample subjected to various values of compressive stress. The effect of tensile stress is not as pronounced.

nence (Sec. 6.18), a positive value of aging coefficient indicates a decrease in these quantities. The aging coefficient of a material is usually obtained by holding the material at a slightly elevated temperature for a certain number of hours. An accepted laboratory method of determining this coefficient is to take data before and after holding the material at 100 C for 600 hr.

Aging is of importance in apparatus because it causes a deterioration in magnetic qualities, with a consequent increase in magnetizing current and core loss. In devices such as magnets, contactors, or brakes an increase in the hysteresis loop means an increase in remanence, which may cause an armature to "stick" closed.

6.21   EFFECT OF DIRECTION OF THE GRAIN

Electrical strip steels have been developed that have considerably different properties, depending on the direction of the flux relative to the direction of rolling. Strip steel, which is rolled in a continuous mill, must not be confused with sheet steel, which, during finishing,

is alternately rolled along the sheet and then across it. Fig. 6.10 shows the saturation curves on a strip steel "with grain," at "cross grain," and at 45° to the grain. Cross-grain pieces also have higher hysteresis loss and it is for this reason that the Epstein test specifies that one-half the samples be taken with the grain and one-half across the grain. The magnetic cores for some transformers are wound from coiled strip so that the flux direction is aligned with the grains.
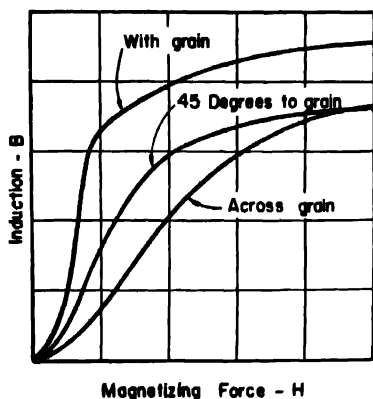
Fɪɢ. 6.10. Magnetization curves for 3 per cent silicon cold-rolled strip steel when tested "with grain," "across grain," and at 45° to grain.

6.22   EFFECT OF TEMPERATURE

Any ferromagnetic material will lose its magnetism if heated to a high enough temperature. The temperature at which this occurs is known as the *Curie point*. It is 770 C for iron, 358 C for nickel, and 1120 C for cobalt, which has the highest known value. For some metals the Curie point lies near a temperature of absolute zero. The relative magnetization under a given field decreases as temperature approaches the Curie point, as illustrated in Fig. 6.11. Sometimes the curve on cooling lies somewhat below this curve, and, in rare cases, is not parallel to the curve for heating.

Abnormal thermal expansion characteristics often occur in metals near the Curie point because of the change in atomic forces associated with ferromagnetism. The medium nickel alloys (30 to 70 per cent Ni) decrease in expansion coefficient and then increase when cooled through their Curie point. This appears to be the result of superposing "magnetic" expansion on the thermal contraction, thus suppressing the normal change.

Small temperature increases only slightly affect the magnetic properties of iron and iron-silicon alloys. The permeability is usually improved, and the hysteresis and eddy-current losses are decreased. The core losses continue to decrease as the temperature approaches the Curie point, and, for medium and high inductions, the permeability reaches unity at this point.
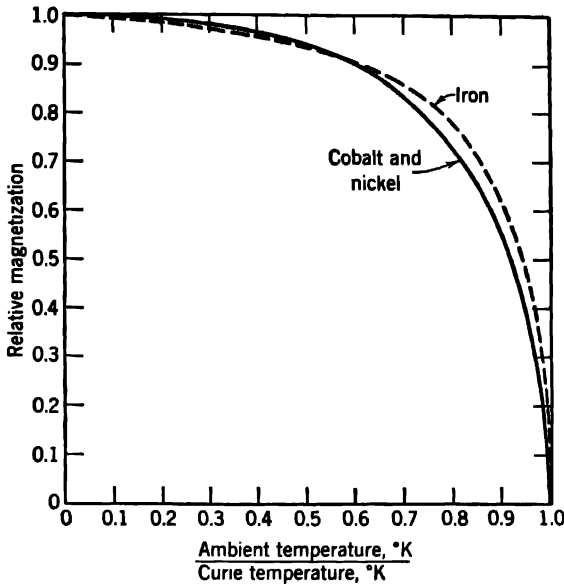
Fig. 6.11. Relative magnetization vs. temperature (as a ratio to curie point)
for three metals.

6.23 EFFECT OF HEAT TREATMENT

The magnetic properties of all magnetic materials are largely dependent on the type of heat treatment they receive. Annealing is usually accomplished in an inert or reducing atmosphere and tends to remove the carbon and to relieve internal elastic strains, thus reducing the area of the hysteresis loop and altering the saturation curve (see Fig. 6.12). Strains not affected by heat treatment are those caused by impurities and magnetization. Since impurities disrupt the orderly arrangement of the atoms and set up lattice strains, freedom from dissolved impurities is very important. There are also strains set up by magnetization, the change in length being called "magnetostriction." These strains are positive with magnetization for some materials, negative for others. In iron, magnetostriction is different for different crystal directions.

6.24 DEMAGNETIZING

It is frequently necessary to demagnetize iron. A common application occurs with the use of magnetic chucks, where it is necessary to demagnetize the chuck and perhaps a large solid section of material in order to remove the work. Demagnetization is accomplished by
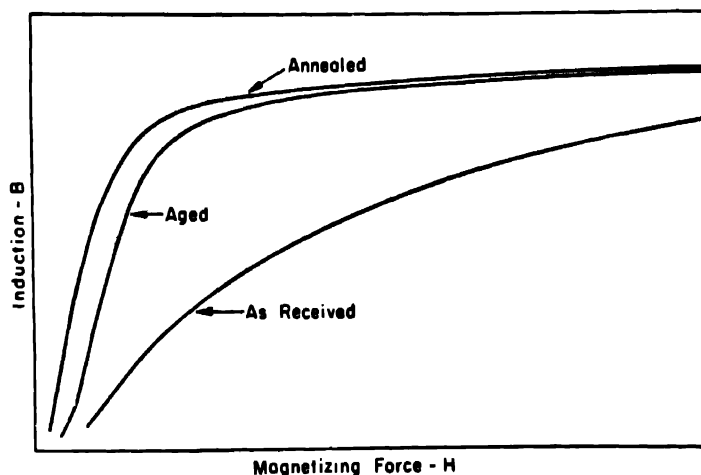
FIG. 6.12. Magnetization curves for Armco ingot iron as received, after 2 weeks aging at 100 C, and after annealing in a hydrogen atmosphere. Note that the intrinsic saturation is the same in each case.
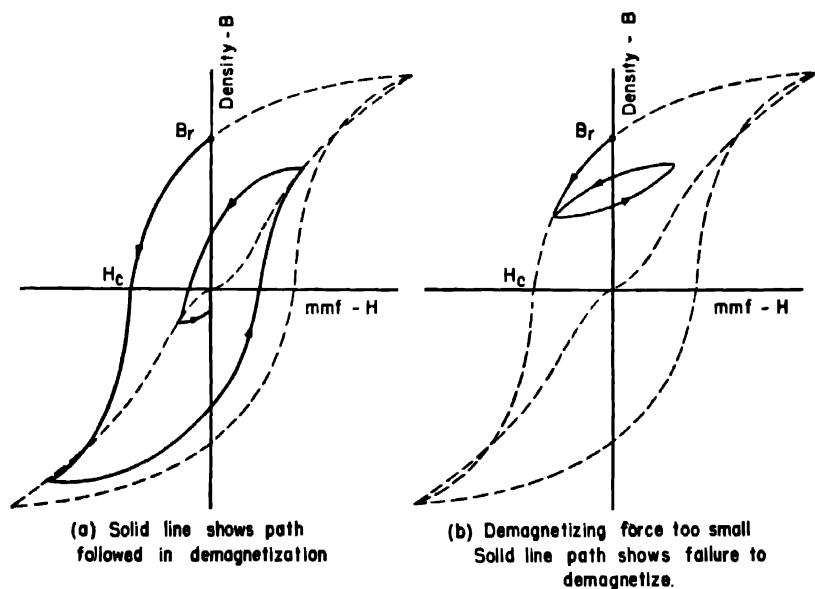
FIG. 6.13. Magnetization paths followed in (a) successful and (b) unsuccessful demagnetization cycles. In the successful cycle the demagnetizing *mmf* is greater than the coercive force at each half cycle, but less than the *mmf* value for the previous half cycle.

applying a field that produces a flux as high or higher than the remanence flux existing in the body. This flux is then reversed to a negative value, which is only slightly less than the previous positive value. The current is then successively increased and decreased, the maximum amplitude being reduced on each reversal until a small value of current, perhaps 10 per cent of the original value, is attained. Fig. 6.13a shows the path traced out during a demagnetizing cycle such as the one described. Fig. 6.13b shows what may occur if only a small mmf is applied to a body having high remanence flux. The efficiency of demagnetizing depends not so much on the total time consumed as on the rate at which the demagnetizing current is changed. For solid materials it is often impossible to get good demagnetizing results if a frequency as high as 60 cycles is used, because eddy currents prevent the penetration of the flux; a *minor-hysteresis* loop is obtained, which still leaves the material magnetized.

6.25   EFFECT OF IRON IN A-C CIRCUITS

Saturation Curve. The saturation curve given for 60-cycle alternating current is somewhat lower than the curve obtained with direct current. This is due to the shielding effect of the induced eddy currents.
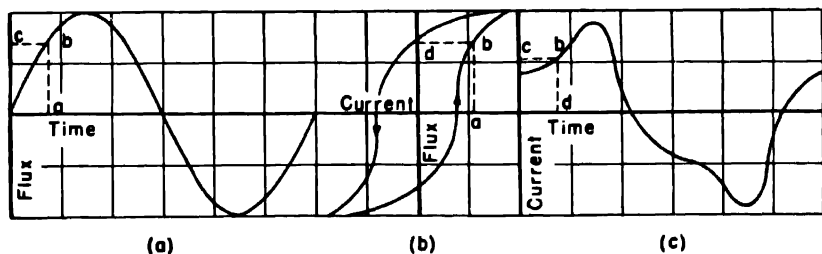
Fig. 6.14.   (a) The harmonic flux wave of a transformer core. (b) The hysteresis loop. (c) The excitation-current wave drawn from corresponding values from curves a and b, as shown.

Third Harmonic. If a sine wave of voltage is applied to a transformer, the resulting current flow is not usually a sine wave but is quite unsymmetrical. Fig. 6.14a shows a sinusoidal flux density wave corresponding to normal sine-wave excitation. The number of amp turns, and therefore the current which must flow at any instant to produce the required flux, is easily determined by reading the corresponding values *cb* and *bd* from Figs. 6.14a and 6.14b, respectively.

The only precaution to be observed is that the ascending part of the loop should be read for the ascending part of the flux-density wave and the descending part of the loop for the descending part of the flux-density wave.   The current wave so drawn (Fig. 6.14c) includes the hysteresis-loss component of current as well as the wattless component of the exciting current.

Analysis of the magnetizing-current wave shows that it contains a third harmonic which is as much as 50 per cent of the fundamental for a large (1000 kva) high-core-density transformer and is about 20 per cent for a 50 kva unit.   Higher multiple harmonics are also present.

Inrush Current.   The residual flux that remains in a magnetic circuit can cause very high currents to flow when the transformer is switched on the line.   In a good magnetic circuit such as may be found in a wound core transformer, this residual may be as much as 70 per cent of the maximum flux density attained throughout a cycle. This residual flux can cause transients which are 300 to 400 times the normal magnetizing current.

6.26   EFFECT OF IMPURITIES AND ALLOYING ELEMENTS ON ELECTROMAGNET MATERIALS

Electromagnet materials are termed "magnetically soft," because they have low residual induction following application and removal of a magnetic field.   The magnetic qualities that are usually specified or evaluated for use of ordinary industrial electromagnet materials are: (1) saturation curve and intrinsic saturation, (2) hysteresis loss, (3) eddy-current loss, and (4) maximum permeability.   The order of importance to the user depends largely on the application. In addition, there are many other qualities that must be considered, some of which are: (1) cost; (2) mechanical properties such as strength, ductility, warping, and distortion; (3) manufacturing properties such as drawing, brazing, welding, and machining qualities, and effect on die life; (4) electrical resistivity, which is one of the factors determining eddy-current loss; (5) thermal conductivity; (6) aging characteristics; (7) corrosion resistance; and (8) initial permeability.

The most common impurities in iron are carbon, oxygen, nitrogen, manganese, sulfur, and phosphorus.   These impurities cause, in general, a decrease in permeability and an increase in hysteresis loss.

A very slight amount of carbon reduces the permeability tremendously, lowers the saturation point, and increases the area of the hysteresis loop, which causes an increase in coercive force and a de-

crease in residual induction. The form in which carbon appears, that is, as cementite or graphite, modifies its influence on magnetic properties.

Sulfur has the greatest detrimental effect, next to carbon. Even very small amounts are harmful.

Phosphorus and oxygen also lower the permeability and increase the hysteresis loss, and attempts are made to minimize their percentages.

Very small amounts of manganese are only slightly harmful. About 0.5 per cent manganese causes the same hysteresis loss as 0.03 per cent sulfur.

Copper is often added to steel to increase its corrosion resistance. In amounts up to 0.5 per cent it has little effect on magnetic properties.

Silicon is the most important nonmagnetic element with which iron is alloyed for sake of magnetic properties. The resistivity of iron is increased approximately 11 microhm-cm for each per cent increase in silicon. Since the resistivity of pure iron is about 10 michrom-cm, the addition of 1 per cent of silicon will double the resistivity, thus reducing the eddy-current loss considerably. Silicon also improves the permeability at low inductions, decreases the intrinsic saturation, and decreases the hysteresis loss. The magnetic improvement is due principally to the elimination of the harmful effects of oxygen and to the reduction of carbon to its less harmful graphitic form. Silicon also reduces aging to a negligible figure. Aluminum is more powerful than silicon as a deoxidizer and has about the same effect on the mechanical properties of iron. Since the resultant magnetic properties are not quite as good, however, aluminum is seldom used as an alloying element for magnetic irons.

6.27 SILICON STEELS

The silicon steels form the most important group of magnetic materials for a-c applications, such as transformers, generators, motors, and relays. The term "electrical sheets" is a trade name for iron and steel sheets used in the manufacture of punchings for laminated magnetic circuits and usually refers to silicon sheet steels. The manufacture of lamination steels for electrical purposes has become very standardized. Names of the standard grades are shown in Table 6.4. Losses and strength generally decrease with increase in silicon content.

Armature. This is the lowest cost mill-annealed steel that can be bought with a core-loss guarantee. Its surface condition may not be

Table 6.4   Types of Silicon Sheets

Name	Approx. Silicon, per cent	Resistivity, microhm-cm	Core Loss, 60 Cy, at B − 15,000	Per Cent of Sheet Losses		Cost per Lb, per cent *
				Eddy Current	Hysteresis	
Field	0.1 to 0.35	16	6.7	..	..	100
Armature	0.25 to 0.75	19	4.5	55	45	109
Electrical	1.0 to 1.5	25	3.9	53	47	122
Motor	2.5 to 3.0	48	2.8	52	48	158
Dynamo	3.5 to 4.0	54	2.3	41	59	197
Transformer	4.5	65	2.0	35	65	220
Special transformer	6	..	1.3	..	..	320

* Costs comparisons are in production quantities as of Apr. 30, 1946.

uniform. It is used in d-c machines or in small apparatus for short duty. It has good machining qualities and can be deep drawn if normalized.

Electrical. This is the lowest grade mill-annealed steel with reliable core loss and mechanical properties. During rolling, considerable care is taken to obtain a smooth surface free from loose and detachable scale. Its most important applications are in relays and fractional horsepower and small railway motors, where its higher saturation limit makes it preferable to the higher silicon

Motor. This grade is used for general-purpose applications where low losses and fairly high magnetizing currents are required. It is the highest grade of silicon steel that has reliable mechanical properties. It is used in fractional horsepower motors,· induction motors, synchronous and d-c machines, and for general purpose a-c control apparatus.

Dynamo. This grade is used where high efficiency and low losses are required, but, since it is somewhat brittle, it is employed in rotating apparatus only where low stresses are involved. It is used in high-efficiency apparatus and lower-grade transformers.

Transformer. There are several grades of transformer steel made to have low losses, without particular regard to mechanical properties. Because of their high silicon content, these steels are too brittle for application in rotating apparatus.

6.28   OTHER IRONS AND STEELS

Ingot Iron. This iron is the purest form of iron obtained commercially. The American Rolling Mill Company ingot iron, known as Armco iron, is guaranteed to be 99.85 per cent pure. Its intrinsic

saturation is very high, as shown in Fig. 6.7. It can be worked mechanically, such as by rolling, but only in certain temperature ranges. If worked outside these limits, it becomes brittle and cracks. This iron also has poor aging qualities. It is used wherever advantage can be taken of its very good magnetization curve and high saturation. It is commonly used in pole faces, in frames of d-c machines, and for time-delay relays in control apparatus. Its resistance is low, 10.7 microhm-cm.

Wrought Iron. The better grades of wrought iron are often known as Norway iron or Swedish iron. They are widely used in relays after being annealed to reduce hysteresis and to prevent aging.

Mild or Low-Carbon Steel. Open-hearth steel of low-carbon content has fairly good magnetic properties and is used quite extensively as a magnetic material. It is even made into electrical sheets of ordinary grade but is, of course, inferior to silicon steel in core losses and aging, though it is superior in magnetization (more flux for the same mmf) and is lower in cost. This steel is used extensively for d-c solenoids, magnetic brakes, and clutches. The frames of d-c machines which were formerly made of cast iron are now largely made of rolled and welded soft steel plates.

Cast Iron. Cast iron has a very poor magnetization curve but is used in magnetic circuits principally because of the advantages it offers in manufacturing.

Cast Steel. Cast steel has a good magnetization curve and is used on d-c machines where high mechanical strength is required. All the above irons and steels require an annealing treatment in order to obtain best magnetic quality.

6.29 FERROMAGNETIC ALLOYS

Nickel-Iron Alloys. Alloys of nickel and iron have a wide range of magnetic properties. The three curves on the extreme left in Fig. 6.7 show the particular properties that some of these alloys possess. In general, they have high permeability and low hysteresis loss at low magnetizing forces. Most of them are very sensitive to mechanical strain and usually require special heat treatment after all mechanical operations have been completed.

The most common materials in this class are Permalloy and Mumetal. Permalloy is the name applied to a number of nickel-iron alloys with high nickel contents. They are used for the continuous loading of submarine cables and in loading coils for land lines. Mumetal (74–78 per cent Ni, 4–5 per cent Cu, 1.5–2 per cent

Cr, bal. Fe) is similar in properties to the Permalloy which has 78 per cent nickel. It has higher initial permeability and lower coercive force than Permalloy, however. Supermalloy, a high purity alloy, with 79 per cent Ni, 5 per cent Mo, 5 per cent Fe, and 0.5 per cent Mn, has very much higher initial permeability and maximum permeability than Mumetal. Its heat treatment is critical and it is sensitive to mechanical strains. Another new material of this class is Moly-Permalloy, which retains high μ to very thin gages better than any other alloy.

An alloy of about 47 per cent nickel balance iron has been developed as a high permeability alloy for radio and other applications where magnetizing forces are low, and high field strengths are involved. It is extensively used in current transformers, reactors, relays, and instruments. It is known by such trade names as Hypernik, Nicaloi, Audiolloy, Carpenter "49," Allegheny "4750," Coppernick, and 50-Permalloy. Very pure Nicaloi and Permanorm have a square hysteresis loop of importance to some applications. Permalloy with 65 per cent Ni develops almost the same characteristics with a special "magnetic anneal." Monimax and Sinimax are new materials of this class developed for ultra-high frequencies. They retain their magnetic properties down to very thin gages (0.001 in.). Monimax contains 47 per cent Ni, 3 per cent Mo, and Sinimax contains 43 per cent Ni, 3 per cent Si, both with balance iron and low impurities.

Iron-Cobalt Alloys. The addition of cobalt up to 36 per cent raises the saturation point of iron (see Fig. 6.7). These alloys are therefore used wherever very high densities are required such as in the pole pieces of electromagnets. They also have constant permeability over a wide range of flux densities and are quite brittle when cold. The 50 per cent cobalt-iron alloy is known as Permendur. Others are vanadium Permendur with 2 per cent vanadium, 50 per cent cobalt, balance iron, and Hiperco, a 35 per cent cobalt 0.5 per cent chromium iron alloy. Their price is relatively high, manufacturing control is difficult, energy losses are high, and use of the high saturation values requires high field strengths.

6.30   POWDER MATERIALS

Pure iron, the Permalloys, and Mumetal have been prepared by the powder method. These products usually have lower magnetic properties, permeability, and saturation than the same alloys produced by conventional means.

A group of nonmetallic materials, known as "ferrites," or "ferrospaniels," may also be produced by the powder method, although they have been made by extrusion. They are mixtures of inorganic salts of the hypothetical acid $HFeO_2$, which usually crystallize in the cubic system. The ferrites of copper, magnesium, and nickel are magnetic; those of zinc and cadmium are nonmagnetic. Mixtures of them permit combinations having Curie points as low as 100 C, and lower values may be developed. Zero magnetostriction products may also be obtained. Mixtures made to have high initial permeability at room temperature have values ranging from 1000 to 4000, several times less than for the magnetically soft materials. The electrical resistance, however, is from 100 to 10,000 microhm-cm (higher when ferrous ions do not exist) which results in low eddy-current losses for frequencies to a million cycle/sec. They are therefore useful in ultrahigh frequency electronic equipment.

6.31   FEEBLY MAGNETIC MATERIALS

Although these materials are not in themselves useful as electro-magnet cores, they may be important in such designs to provide structural members which are "nonmagnetic" (permeability of 2 or less). They are often employed to reduce eddy-current heating and to reduce energy losses of such parts as rotor-coil binding wire, shafts, bolts, fillers, and pole-support castings.

Austenitic 18-8 stainless steel, and steels having 14 per cent manganese with 1.25 per cent carbon, 10 per cent manganese with 8 per cent nickel and 0.3 per cent max carbon, 14 per cent manganese with 3 per cent nickel and 0.7 per cent carbon, and 18 per cent manganese with 1.5 per cent nickel and 0.3 per cent carbon are typical feebly magnetic materials supplied in wrought form. All have poor corrosion resistance except the stainless steels. The high-carbon manganese steels are also hard to machine. As castings, Nomag with 11 per cent Ni, 5.2 per cent Mn, 2.7 per cent C, is the only cast iron in use; 14 per cent Mn with 1.2 per cent C is recommended for steel castings where grinding is required; 10 per cent Mn, 6 per cent Ni, and 0.25 per cent C and 18 per cent Mn, 1.5 per cent Ni, and 0.3 per cent C are steel alloys recommended when machining is involved.

PERMANENT MAGNETS

by S. C. HOARE *

6.32 PERMANENT MAGNETS

A permanent magnet is a source of *magnetic potential* that requires no external source of power as does an electromagnet. It is made from "magnetically hard" materials. Hard magnetic materials differ from soft magnetic materials in that a larger applied field, or magnetizing force, is needed to induce the same amount resultant magnetism in the material. They also require a high opposing magnetic force to remove the resultant magnetism, whereas soft magnets need only slight forces. The permeability, μ, is high for soft magnets and low for permanent magnets. If they are protected from demagnetizing influences, their capacity to exert magnetic forces or provide magnetic flux will persist indefinitely.

Hardened unalloyed carbon steel was the best permanent-magnet material known until early in the present century, when it was found that stronger and more stable magnets could be made of tungsten steel or of chromium steel. In 1920 Honda announced the development of cobalt-magnet steel, which had 3 times the coercive force of tungsten or chromium steel and about the same residual induction. Like all the preceding materials, except lodestone, this material was a carbon steel which had to be quenched in oil or water from a high temperature in order to develop its permanent-magnet qualities.

In 1930 the first of the age-hardening permanent-magnet alloys was produced. These materials differ from carbon steel in that they contain no carbon except as an undesirable impurity. Their final heat treatment is usually a slow cooling at a controlled rate, or a prolonged heating at a temperature not higher than a dull-red heat. Quenching is sometimes used as a preliminary treatment to bring the constituents into a solid solution in the alloy. In this condition the alloy is most workable but it has very poor magnetic properties. The low-temperature heating or precipitation treatment increases the hardness of the alloy, in addition to developing its permanent-magnet qualities. Alnico belongs in this class of materials, and its precipitation treatment usually consists in a controlled

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cooling from a high temperature rather than in a prolonged heating.

Oxide magnets belong in a third class of permanent-magnet materials. They include lodestone and sintered oxide. One of the latter materials, a mixture of iron and cobalt oxides (Vectolite), is pressed and fired at a high temperature so that the particles unite and diffuse into each other without actually melting. It is subsequently heat treated in a magnetic field. This material is used because of its light weight and high coercive force, which make it suitable for the moving elements of electrical instruments.

6.33 THEORY OF PERMANENT MAGNET ALLOYS

The theory of permanent-magnet alloys is far from complete. The usual requirements are that the alloy shall contain one or more ferromagnetic materials and one or more nonmagnetic materials. The function of the nonmagnetic materials is to distort, or strain, the crystal lattice of the ferromagnetic material, since a strained lattice appears to be essential for a high coercive force. Very limited success has been achieved in predicting the magnetic properties of alloys from theoretical considerations. Since the best permanent-magnet alloys contain five or more metals, the possible number of combinations of ingredients and heat treatments is enormous. Eventually, an increase in theoretical knowledge should simplify the present trial-and-error methods of development.

6.34 HYSTERESIS LOOP

The magnetization curve illustrated by the dotted line in Fig. 6.15 is obtained by subjecting a closed ring of Alnico 2, which has not been magnetized before or which has been carefully demagnetized, to a gradually increasing magnetic force. This may be accomplished by gradually increasing the electric current in a coil of wire wound on the material. Point B_m represents the peak saturation of magnetic induction in gausses (maxwells per sq cm of cross section) when the material is subjected to a peak magnetizing force of $+H_p = 2000$ oersteds (gilberts per cm of length or 4040 amp turns/in.). Further increase in H will, of course, result in an increase in B, in accordance with the air line. The intrinsic saturation, however, remains fixed and is $B_i = B_p - H_p$.

If the magnetizing force, H, is gradually reduced from the highest applied value, $+H_p$, to zero, the resultant magnetization in the material decreases to $B_r = 7300$ gausses, known as the *residual induction*. If the magnetizing force is then reversed (by reversing

the current in the coil of wire) and increased in the negative direction to $-H_c = 560$ oersteds, the resultant magnetization in the material is reduced to zero. The value $-H_c$ of the demagnetizing force at this point is known as the *coercive force*. Increasing the demagnetizing force to $-H_p$ results in changing the value of B from positive to negative, or changing the polarity of the material.
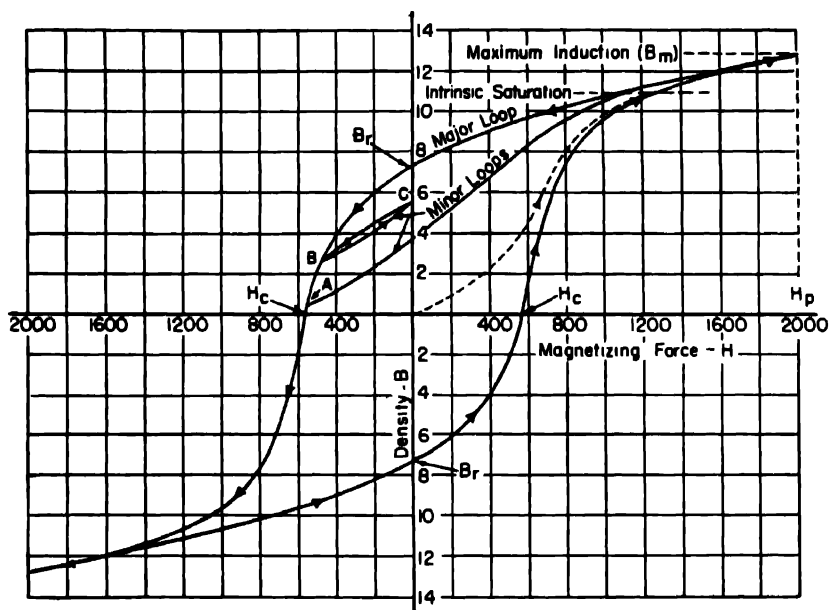
Fig. 6.15. Hysteresis loop for Alnico 2.

The negative B_m corresponds in value to the positive B_m. The right-hand side of the curve is obtained by repeating the process but starting with negative H_p. The solid lines of Fig. 6.15 form a closed loop known as the *hysteresis loop*.

Minor Loops. Consider now that at point A on the upper branch of the loop of Fig. 6.15, the cyclic variation of H is interrupted, and H is now caused to increase in the positive direction. Induction in the alloy will now return along a new curve, which is part of a *minor loop*. Minor loops can be obtained from any point on the curve and can be of any length less than that of the major loop. The permanent magnet designer is concerned chiefly with short minor loops such as B-C.

6.35   DEMAGNETIZATION AND EXTERNAL-ENERGY CURVES

The *demagnetization curve* used for permanent-magnet design is that portion of the hysteresis loop in the second quadrant. This curve, from $+B_r$ to $-H_c$, is drawn in enlarged form in Fig. 6.16. The products of corresponding values of B and H at any point on the demagnetization curve are plotted on the right of Fig. 6.16, forming the *external-energy* curve.
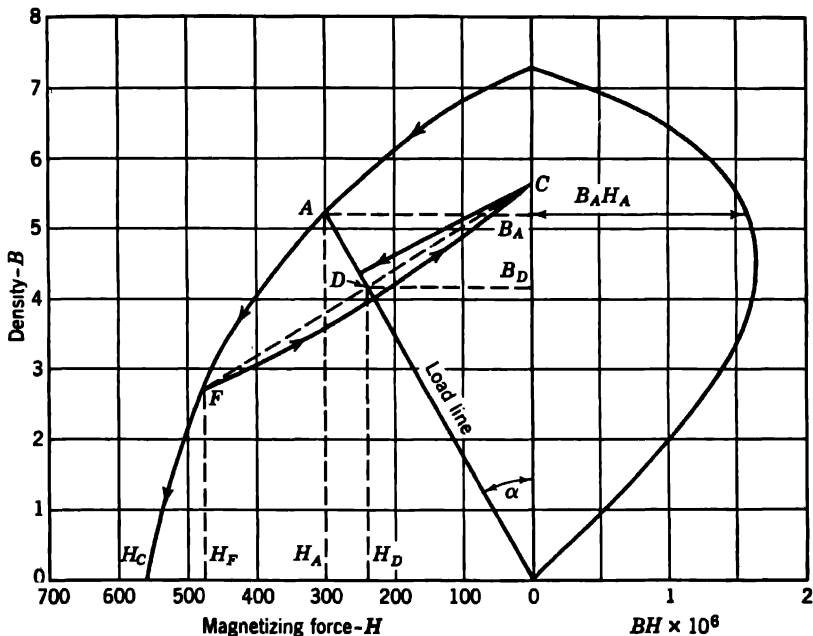
Fɪɢ. 6.16. On the left is the demagnetization curve for Alnico 2, the second quadrant of Fig. 6.15. On the right is the external-energy curve obtained by multiplying $B \times H$ for each point along the demagnetization curve.

The residual induction, B_r, is a measure of the ability of a magnet to retain its magnetism when it is not subject to adverse treatment. It is the magnetic induction corresponding to zero magnetizing force. This value of B indicates the number of flux lines per sq cm that the magnet can maintain in a closed magnetic circuit. The higher the value of residual induction, the smaller the cross section of the magnet required to maintain a given total flux.

The coercive force, $-H_c$, is the demagnetizing force required to reduce the induction to zero. In general, the higher the coercive

force, the shorter the magnet required to maintain a given air-gap flux density.

The external-energy curve is a graphical representation of the variation of available potential energy that the magnet can furnish for external use at various operating flux densities. If B and H represent, respectively, the flux density in *gausses* and the demagnetizing force in *oersteds*, the expression $(B \times H)/8\pi$ represents the energy in ergs that each cu cm of magnet material can supply for external use in the air gap. The product of B and H (usually expressed in *gauss-oersteds*) is, therefore, proportional to the magnetic external energy.

The external-energy curve signifies the optimum magnetic flux density at which a permanent magnet will give the maximum energy output. Therefore, if a permanent magnet is to have a minimum volume, the design factors must be so controlled that the magnet will operate at this optimum flux density.

6.36   DEMAGNETIZING INFLUENCES

After a magnet has been fully magnetized and removed from the field of the magnetizer, but kept in a closed circuit with a soft-iron keeper across its poles, it will have the maximum residual induction it can maintain without outside influence. If the keeper is removed (open circuited), the magnet will become partially demagnetized, and the value of the magnetic flux density will drop to a lower point on the demagnetization curve. This value will remain constant until the magnet is subjected to further adverse effects such as heat, vibration or impact, stray magnetic fields, or changes in the external magnetic circuit such as an increase in air-gap length.

6.37   MAGNETIC CIRCUIT CONTAINING AN AIR GAP

The load line, OA in Fig. 6.16, is drawn so that the tangent of the angle, α, is equal to the reluctance of the air gap and the leakage in terms of their physical dimensions. The magnetic circuit made up of a closed magnet in series with the air gap will operate with flux indicated at point A. The product $B_A H_A$ is proportional to the energy per unit volume of magnet material stored in both the air gap and leakage flux.

The point A on the demagnetization curve of Fig. 6.16 is the initial *knockdown* of the magnet due to the demagnetizing effect of the air gap. If now the magnet is demagnetized further, either by temporary increase of the air-gap length or by temporary applica-

tion of a d-c field, the induction falls, say to point F. Upon removal of the temporary demagnetizing force, the induction rises not to point A but to point D at the junction of a minor loop and the load line. Actually, the induction will fall slightly lower than D on the load line, but, because of the small "spread" of the minor loop in this quadrant, the induction may be considered for practical purposes as falling back along the axis of a minor loop line FC. .

The minor loop illustrates the demagnetizing protection given by magnetic knockdown; by reducing the magnet strength, the stability of the magnet is increased. Taking the initial condition represented by point A, any temporary increase of demagnetizing force beyond H_A results in a permanent decrease in induction. A temporary knockdown to H_F gives the magnet a "reserve magnetizing force," not of $H_F - H_A$ but of $H_F - H_D$. The permanent knockdown in induction to obtain this protection is $B_A - B_D$. After this permanent knockdown there will be no permanent changes in induction until a total demagnetizing force in excess of H_F is applied. A force greater than H_F will immediately initiate a new minor loop lower in the quadrant. The history of loading thus determines the operating point and the external energy at that point (proportional to $B_D H_D$) is considerably less than at point A.

In a magnet having a uniform area of cross section throughout its length, leakage from the magnet surface results in changing values of H and B along the length. Values of B will be relatively great and values of H small in the neutral region, whereas the reverse will occur at the poles. These variations in B and H are often minimized by giving the magnet a graded cross section, but at best a single load line can represent only average conditions of B and H. The great value of the load line is in showing that the final average operating point lies on this line, following temporary magnetizing or demagnetizing influences—its actual position being determined by where the line is cut by the particular minor loop. Coordinates of the point denote average operating conditions of H and B.

Maximum economy of material will be had where the dimension ratio of length to section area causes the load line to intercept the demagnetization curve at the level of BH max on the external-energy curve. This condition will result in the minimum volume of material for a given output. For this economic condition the magnet will have also the best balance of energy throughout its entire length. When the magnet is to be knocked down for oper-

ation on a minor loop, operation at the point of maximum energy is no longer possible, and some lower value of external energy must be accepted as the highest obtainable with knockdown protection. Consequently, knocked-down magnets will usually require more than the economic volume of material to have reserve magnetizing force. The point may also be made here that all magnetic materials vary in magnetic quality from one lot to another. In design of magnets to be produced in quantity, some allowance must be made for this variation. It may be most economical of material to permit a small percentage of rejects for low strength.

Where magnet space is at a premium, it is generally the best practice to design the magnet in the economic proportions of length to sectional area. The economic magnet seldom is the best magnet, however, and where space is not at a premium, substantial gains in magnetic strength and stability can be had with an additional length of magnet. It will be found that there is an optimum length (greater than the economic length) where the magnet will deliver the maximum flux. This occurs where the product of the magnet's H and its length L is at the maximum value. Generally, the optimum length is about twice the economic length, but the individual magnet system should be examined in this respect. For the optimum length, the load line will cut the demagnetization curve at a point well above the economic level, which results in a greater protective length of minor loop with knockdown.

Methods of applying these magnetic characteristics to problems of analysis and design are straightforward. Simple and symmetrical magnetic circuits can be calculated to an accuracy within a very few per cent. Complicated arrangements do not permit precise treatment of leakage reluctance, and either an estimate or a graphical solution may be used, the accuracy of the method depending upon the need.

6.38 AGING

Aging (of a permanent magnet) is the process of normal or accelerated change, under continued normal or specified artificial conditions, in the strength of the magnetic field maintained. The change in field strength due to aging is usually expressed in per cent.

Aging may be of two types, metallurgical or magnetic. Each type may occur either singly or in combination with the other.

Metallurgical aging is a result of a change in the metallurgical condition of the magnet, which changes its ability to maintain itself in a magnetized condition. This change may begin immediately after the magnet is hardened and, at room temperature, may continue at a diminishing rate for a long period of time. High temperatures usually accelerate these metallurgical changes. Hence, most permanent-magnet materials are stabilized by baking for about 24 hr at a temperature between 100 and 200 C. The change may also be accelerated in some materials by cooling below room temperature, by cyclic temperature changes, and possibly by mechanical vibration. Magnets that have been metallurgically aged cannot be restored to their original strength by remagnetization.

Magnetic aging is the result of some external influence which causes a change in the strength of the magnetic field being maintained by the magnet, but does not alter the metallurgical condition of the magnet as far as its magnetic properties are concerned. Magnets that have suffered only magnetic aging may be restored to their original strength by remagnetization.

The four main causes of magnetic aging are: (1) presence of strong external magnetic fields; (2) mechanical vibration (when the aging does not result from metallurgical changes induced by vibration); (3) changes in the external magnetic circuit, such as increasing the air-gap length or removing the "keeper"; and (4) temperature conditions (when the aging does not result from metallurgical changes induced by temperature).

After metallurgical stabilization has been completed and a permanent magnet is magnetized, heating and cooling may cause some demagnetization. Retraceable magnetic characteristics are obtained only after from one to four temperature cycles. Subsequent cycles result in no further permanent changes as long as the maximum temperature reached in the first cycle is not exceeded. The magnetic curves for Alnico are retraceable for temperatures from −200 C up to 300 C. Sintered oxides and Silmanal, however, are not retraceable for temperatures over 50 C. The magnetic curves for cobalt or chrome steels are not retraceable above 100 C. The strength is always slightly greater at low temperatures (see Fig. 6.17). The coercive force of sintered oxides decreases rapidly with increasing temperature, so that they must not be used in applications which combine temperatures above 70 to 80 C with strong demagnetizing fields. Temperature tests are always made in con-

nection with new applications of the recently developed magnetic materials to assure proper performance.

Strains set up by vibration or impact produce varying amounts of magnetic instability of the molecular structure, caused by the breakdown of feebly oriented molecular groups. A permanent de-
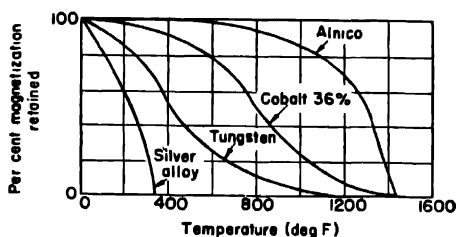
Fig. 6.17. Relative magnetization retained after heating for several materials.

magnetization effect results when a magnet is subjected to sufficient vibration or impact. The remanent induction, B_D, does not return to its original value after the removal of the stresses. A stabilized condition is reached, after which continued vibration or impact of the same magnitude has no further effect. The magnet is then said to be stabilized for these influences (see Fig. 6.18).

The demagnetization effect of stray magnetic fields depends on the coercive force of the permanent magnet material. The higher the intrinsic coercive force, $-H_{ci}$, the greater the resistance to stray
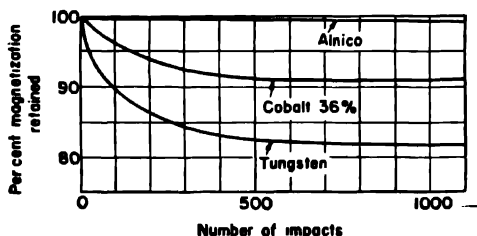
Fig. 6.18. Relative magnetization retained after repeated impacts on bars ⅝ in. x ¼ in. x 10 in.

magnetic fields. Tests on Alnico-2 bar magnets, each ⅝ in. x ¼ in. x 10 in., when subjected to a 50-cycle alternating field of various magnitudes, show a reduction in flux, as indicated in Fig. 6.19.

If steel or other magnetic materials accidentally touch the sides or back of a magnet, they will establish additional poles, thereby

altering the flux distribution of the magnets to some extent. Protective nonmagnetic covers are occasionally used to protect the surfaces of magnets from contact with other magnetic objects.

In many applications, a high degree of stability against demagnetizing influences is required to obtain uniform and consistent operation. Magnets that must resist high heat can be initially subjected to a temperature cycle which duplicates that encountered in actual use. Magnets that must withstand vibration can be initially exposed to vibration similar in range to operating conditions. Through these means, permanent-magnet materials can be stabil-
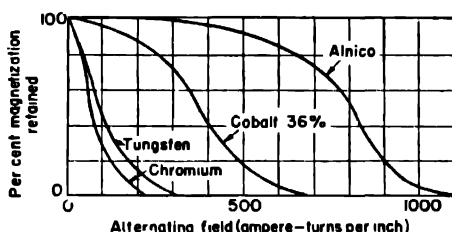
Fig. 6.19. Relative magnetization retained after subjecting bars ⅝ in. x ¼ in. x 10 in. to 50-cycle alternating demagnetizing fields.

ized so that continued application of the demagnetizing influence has no further effect.

6.39 PERMANENT-MAGNET MATERIALS

Hardened Steels. The comparatively low coercive force and external energy available in the various steels requires use of long, slim magnets of rather great volume (for example, the familiar "horseshoe" magnet) to perform the task of a much smaller magnet of the newer alloys. The steels still have a field of application, however, where space is not limited and their lower cost per pound makes them economically attractive.

The demagnetization and external-energy curves for the typical permanent-magnet steels are illustrated in Fig. 6.20 in comparison with Alnico 2. Plain carbon steel has an external energy only about one-half that of Tungsten steel.

A cobalt-molybdenum-iron precipitation-hardening alloy (81 per cent Fe, 12 per cent Co, 17 per cent Mo) marketed as Comol and Remalloy is about equivalent to the 36 per cent cobalt alloy but less expensive. Another precipitation-hardening alloy, known as Vicalloy, with 32–62 per cent Co, 6–16 per cent V, balance iron,

has equal residual induction but higher coercive force and external energy.

Alnicos. These materials are composed mainly of aluminum, nickel, cobalt, and iron, hence their name. Some include additions of copper and titanium. They are high-coercive-force, high-magnetic-energy alloys, and at present there are nine grades: 1, 2, 3,
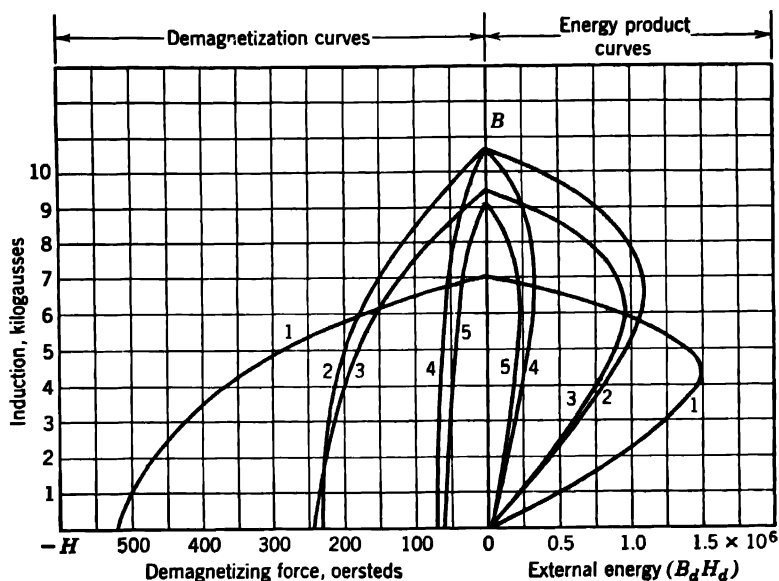
FIG. 6.20. Demagnetization and external-energy curves for several steels. Curve 1, sintered Alnico 2; Curve 2, 42 per cent cobalt steel; Curve 3, 36 per cent cobalt steel; Curve 4, 5 per cent tungsten steel; Curve 5, 3 per cent chromium steel.

4, 5, 5DG, 6, 7, and 12. Each has a different combination of the above elements and different magnetic properties, see Table 6.5.

All grades of Alnico can be cast to shape by pouring the liquid metal from an electric furnace into a sand mold. Upon cooling, the cast magnet is removed from the mold, cleaned, any necessary rough grinding performed, and heat treated. If tolerances closer than the "as-cast" tolerances are required, the magnets are ground and then magnetized. Precision casting is sometimes used to obtain closer tolerances. Sand castings are usually most economical for magnets of simple design and weighing over 15 g.

Where the size of desired steel inserts prohibits casting the insert in the magnet because of its tendency to crack the magnet on cool-

ing, it is possible to copper braze the insert in place during the initial heat treatment by a special process. Copper brazing after heat treatment should not be attempted, as the magnetic properties will be lowered.

Careless handling of cast magnets, particularly the smaller sizes, may result in chipping or fracturing. This is caused by the large crystals, inherent in cast Alnico magnets, orienting themselves at a corner or edge.

Sintered Alnico is well adapted to the mass production of small magnets with intricate shapes. These magnets are produced by pressing a mixture of constituent metal powders in a die to approximately the final shape of the magnet. Holes, slots, or grooves are made parts of the die. The pressed parts are sintered in a hydrogen furnace, after which the magnets are ground, if necessary, and then magnetized. Only Alnicos 2, 4, and 5 are available in sintered form.

Sintered magnets are fine grained and, therefore, have more uniform flux distribution and greater mechanical strength than cast magnets. Sintered Alnico is easily ground, when necessary, but it is nonforgeable.

Demagnetization and external energy curves of the Alnicos are illustrated in Fig. 6.21. The values listed are minimum values and apply to sintered grades, where available, as well as to the cast grades.

Alnico 1 is a general-purpose grade used mainly in sizes above 1 sq in. in section, or where grade 3 may crack.

Alnico 2 has better properties than 1 or 3, but costs more. It is most popular as a general-purpose sintered magnet.

Alnico 3 is the lowest-cost grade available.

Alnico 4 has limited application as a sintered grade where short magnets are subject to open-circuit conditions. The cast grade is used for magnet chucks, clutches, and separators.

Alnico 5 has high external-energy and residual induction and is used where space or weight is at a premium. It has directional properties.

Alnico 5DG is an improved grade of Alnico 5 available in only the cast form. Directional grain growth of the crystal structure in the direction of magnetization in this grade results in the improvement of magnetic properties. It has the highest external energy of any commercial permanent-magnet alloy.

Table 6.5   Magnetic Properties of Some Permanent-Magnet Materials

Magnet Material	Typical Chemical Composition, per cent	Form	Magnetizing Force, H_{max} oersteds	Magnetic Induction, B_{max} gausses	Minimum Residual Induction, B_r* gausses	Minimum Coercive Force, H* oersteds	Minimum External Energy			Maximum Permeability	Commercial Methods of Fabrication
							$(B_d H_d)_{max}$*	Occurs at B	Occurs at H		
Carbon steel	1 C, 0.5 Mn, bal. Fe	Bar	300	14,800	8,600	48	180,000	6000	25	110	Hot forge, machine, punch
Tungsten steel	5 W, 1 C, bal. Fe	Bar	300	14,500	10,300	70	320,000	7400	50	120	Hot forge, cast, machine, punch (thin sections)
Chromium steel	3.5 Cr, 1 C, bal. Fe	Bar	300	13,500	9,000	63	290,000	6000	35	105	Hot forge, cast, machine, punch (thin sections)
36% cobalt steel	36 Co, 3 5 Cr, 3 W, 0.85 C, bal. Fe	Bar	1,000	15,500	9,000	210	936,000	6300	140	35	Hot forge, cast, machine, punch
Alnico 1	12 Al, 20 Ni, 5 Co, bal. Fe	Cast	2,000	12,350	7,100	400	1,300,000	4200	300	14	Cast, grind
Alnico 2	10 Al, 17 Ni, 12.5 Co, 6 Cu, bal. Fe	Cast	2,000	12,600	7,200	540	1,640,000	4500	365	11	Cast, grind
Alnico 2	10 Al, 17 Ni, 12.5 Co, 6 Cu, bal. Fe	Sintered	2,000	12,000	6,900	520	1,430,000	4300	350	12	Sinter, grind
Alnico 3 (cross section under $\frac{5}{16}$" x $\frac{5}{16}$")	12 Al, 25 Ni, bal. Fe	Cast	2,000	12,000	6,700	450	1,380,000	4300	320	12	Cast, grind

Material	Composition	Form									Fabrication
Alnico 4	12 Al, 28 Ni, 5 Co, bal. Fe	Cast, sintered	3.000	11,850	5,200	700	1,200 000	3000	380	6	Cast, sinter, grind
Alnico 5	8 Al, 14 Ni, 24 Co, 3 Cu, bal. Fe	Cast	3.000	15,700	12,000	575	4,500.000	9050	500	18	Cast, grind
Alnico 5	8 Al, 14 Ni, 1 Ti, 24 Co, 3 Cu, bal. Fe	Sintered	3.000	15,500	10,000	575	3,500.000			.	Sinter, grind
Alnico 6	8 Al, 15 Ni, 24 Co, 3 Cu, 1.25 Ti, bal. Fe	Cast	3.000	14,300	10,000	750	3,500 000	7000	475	11	Cast, grind
Alnico 12	6 Al, 18 Ni, 35 Co, 8 Ti, bal. Fe	Cast	3.000	12,800	5,800	950	1,500.000	3000	500	4	Cast, grind
Cunife (under 0.155" diameter)	60 Cu, 20 Ni, 20 Fe	Wire, strip	2,400	8,400	5,400	550	1,500.000	4000	375	8	Cast, cold roll, machine, punch
Cunico	30 Cu, 21 Ni, 29 Co	Strip, rod, wire, cast	3,200	8,000	3,400	660	800,000	2000	400	3.8	Machine, punch, cast, cold roll
Vectolite	30 Fe_2O_3, 44 Fe_3O_4, 26 Co_2O_3	Sintered	3,000	4,800	1,600	1000	600,000	900	670	3	Sinter, grind
Silmanal	86.75 Ag, 8.8 Mn, 4.45 Al	Rod, strip, sheet	20 000	20,830† $B_s = 830$	550	550† $H_s = 6000$	76,000	275	275	1.11	Cold roll, machine, punch

Table 6.5   Magnetic Properties of Some Permanent-Magnet Materials (Continued)

Magnet Material	Form	General Mechanical Properties	Average Density, lbs/cu in.	Tensile Strength, lbs/sq in.	Transverse Modulus of Rupture, lbs/sq in.	Hardness, Rockwell scale	Coefficient of Thermal Expansion, $1°C \times 10^{-6}$ 20 C − 300 C	Resistivity Microhme, per cm per cm^3 at 25 C	Remarks
Carbon steel	Bar	Hard, relatively strong	0.280			C-60		35	High aging and low coercive force offset very low cost except where space permits very large magnets.
Tungsten steel	Bar	Hard, relatively strong	0.292			C-65		35	Highest B_r for lowest cost but generally replaced by chrome steel with slight loss of quality but considerably lower cost.
Chromium steel	Bar	Hard, relatively strong	0.281			C-65		45	Low-cost material for magnets of comparatively good magnetic external energy and uniformity where space or weight is not too limited.
36% cobalt steel	Bar	Hard, relatively strong	0.296		..	C-56-64		76	Used where good magnetic quality, combined with machinability is required, but Alnicos are less expensive.
Alnico 1	Cast, grind	Ha, d, brittle	0.249	4 100	13.900	C-45	12 6	75	General-purpose grade of cast Alnico having good magnet qualities at reasonable cost.
Alnico 2	Cast, grind	Hard, brittle	0.256	3.000	7.200	C-45	12.4	65	Better magnetic qualities than Alnico 1 at slight additional cost.
Alnico 2	Sintered, grind	Hard	0.243	65.000	70.000	C-43	12.4	68	For small or complicated shapes.
Alnico 3 (cross section under ⅝" x ⅝")	Cast, grind	Hard, brittle	0.249	12,000	22,500	C-45	13.0	60	Lowest-cost grade of cast Alnico commercially available.

Alnico 4	Cast, grind	Hard, brittle	0.253	9,100	24,000	C-45	13.1	75	High coercive-force grade of low-cost Alnico. Used where short magnets are required.
Alnico 4	Sintered, grind	Hard, brittle	0.232	60,000	85,000	C-42	13.1	68	For small or complicated shapes.
Alnico 5	Cast, grind	Hard, brittle	0.264	5,450	10,500	C-50	11.3	47	Highest external-energy and residual-flux Alnico. Magnetically directional.
Alnico 5	Sintered, grind	Hard, brittle	0.241	..	..	C-44	11.3	..	Highest external energy of sintered Alnico.
Alnico 6	Cast, grind	Hard, brittle	0.268	23,000	45,000	C-56	11.4	50	Higher coercive force than Alnico 5, with lower residual induction and external energy. Magnetically directional.
Alnico 12	Cast, grind	Hard, brittle	0.264	39,500	50,000	C-58	11 0	62	Highest coercive force of Alnicos. Should be cast to size as material is very difficult to work.
Cunife (under 0.155" in diameter)	Wire, strip	Ductile, malleable	0.311	120,000	..	B-73	14.0	2	Good fabricating properties combined with magnetic hardness. Magnetically directional in direction of working.
Cunico	Strip, rod, wire, cast	Ductile, malleable	0.300	85,000	..	B-95	14 0	32	Readily workable, high coercive-force alloy.
Vectolite	Sintered	Low strength, brittle	0.113	2,600 ‡ 4,000 §			8.5	225 × 10⁶	High coercive-force, low-residual, high-resistivity material. Light weight. Magnetically directional. Permits short magnets with long air gaps.
Silmanal	Rod, strip sheet	Workable	0.325	..	..	B-95	..	19	Extremely high coercive force and permanency. Low residual and relatively high cost. Limited applicability for special purposes.

* Guaranteed minimum values.
† B_i and H_i values are on the basis of intrinsic induction.
‡ Transverse modulus of rupture.
§ When impregnated.

Alnico 6 has higher coercive force and less residual induction than Alnico 5, and also has directional properties.

Alnico 7 has the highest coercive force of these grades, with good residual induction. It is used where high-demagnetization forces are encountered as in motors, generators, and air-gap type devices, and where shortest magnet lengths are desired.
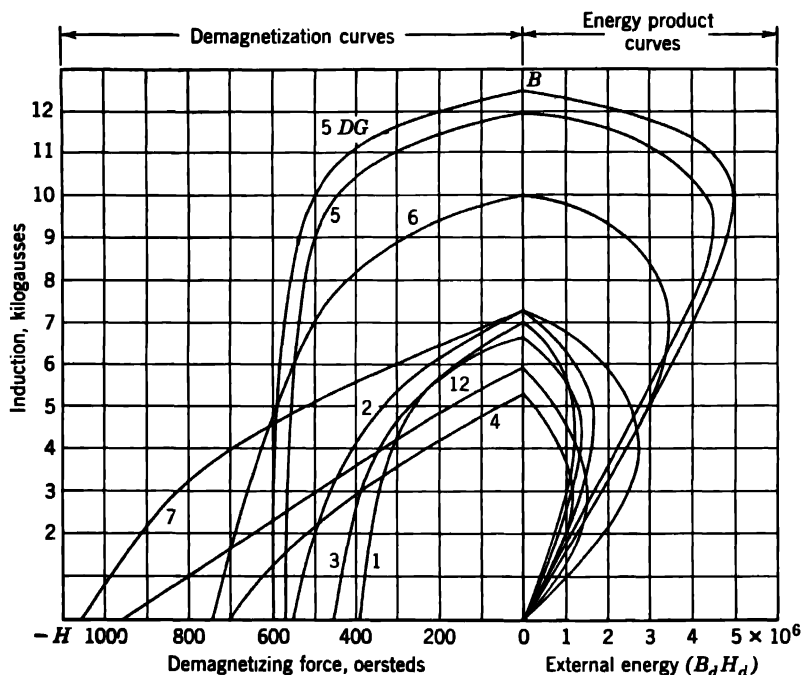
FIG. 6.21. Demagnetization and external-energy curves for various grades of Alnico. Numbers on curves correspond to the Alnico grade numbers.

Alnico 12 had the highest coercive force until the introduction of grade 7. It is also quite brittle and subject to chipping if ground.

Cunife is a copper-nickel-iron alloy that is malleable, ductile, and machinable, even in an age-hardened form. Its magnets are made from wire stock in round, square, or rectangular form. Round magnets are usually furnished in AWG sizes from No. 2 to No. 24 but can be made in other sizes. Best magnetic properties are obtained in round sections less than 0.155 in. diam (see Fig. 6.22). Cunife has directional properties and should be magnetized in the

direction in which it was drawn. Better magnetically in smaller sizes, only magnets of less than 0.250 in. diam are made from cunife. In small sizes it has a tensile strength of about 100,000 psi, and its electrical conductivity is 9.2 per cent that of copper.

Cunico is another copper-nickel-cobalt alloy that is ductile, malleable, and machinable prior to final heat treatment. It has a higher coercive force but a lower residual induction than cunife (see Fig.
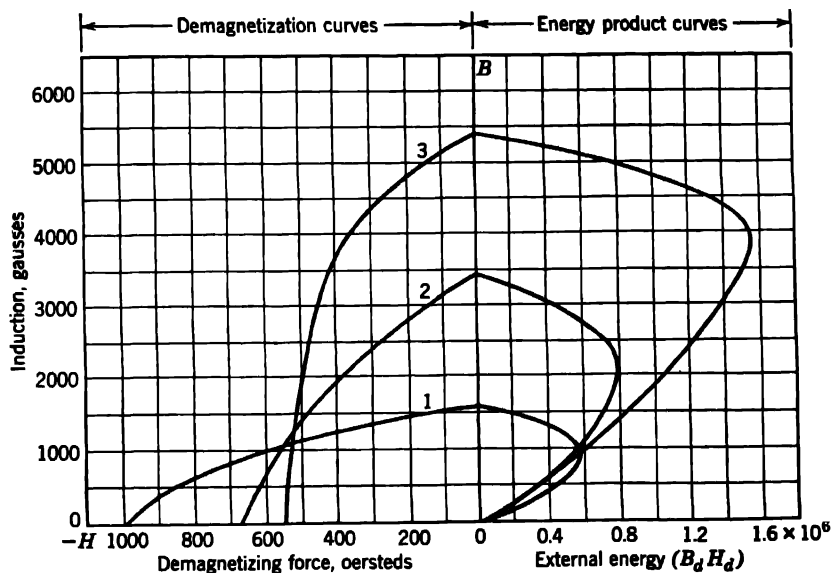
Fig. 6.22. Demagnetization and external-energy curves for Vectolite (Curve 1), Cunico (Curve 2), and Cunife (Curve 3).

6.22). It can be made from rods, strip, and wire, and also precision or sand cast. Magnets from ¼ to 1 in. diam are usually cut and machined from rods. Sizes larger than 1 in. in diam can be cast but will have somewhat lower magnetic properties. It is recommended for magnets of 0.250 in. diam or larger and generally best suited for magnets where a large cross section is needed to produce sufficient total flux. Note the higher external energy and coercive force of cunico and cunife over the hard steels.

Vectolite is a sintered material of iron oxide and cobalt oxide. It is light in weight with a higher coercive force than cunico, cunife, or any of the alnicos excepting Alnico 7 (see Fig. 6.22). It can be ground but is weak mechanically and, therefore, should be sintered

to final size whenever possible. Vectolite has directional properties and must be magnetized along the axis of heat treatment. Because of its high electrical resistance, high coercive force, and low eddy-current loss, it has been used successfully in high-frequency magnetic fields. Rotor magnets, d-c selsyns, tachometer indicators, and other types of moving magnets are other applications.
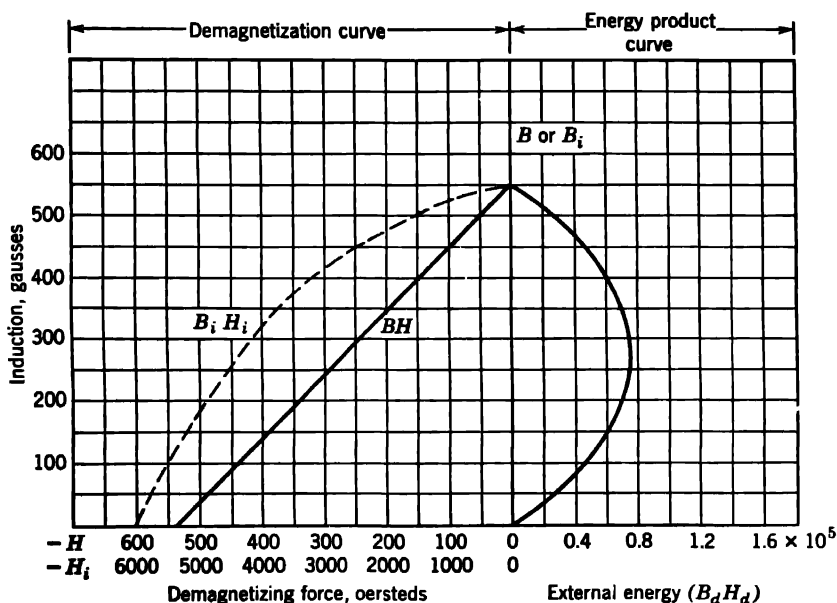
Fɪɢ. 6.23. Demagnetization and external-energy curves for Silmanal. The solid curve is for design. The dotted curve indicates permanency against demagnetization.

Chromium, zinc, tungsten, nickel, and copper oxides have also been used in oxide magnets, but results have not been of commercial importance to date. One combination containing 16 per cent CoO, 34 per cent Fe_2O_3, and 50 per cent Fe_3O_4 gives promise of about twice the external energy of Vectolite and higher residual induction with a sacrifice in coercive force. These materials appear to offer interesting possibilities when manufacturing control can be established.

Silmanal is the name given to a rather expensive alloy of silver, manganese, and aluminum that has unusual magnetic properties for special applications (see Fig. 6.23). It is ductile and malleable and can be machined as readily as soft steel. Magnets are made from

wire, swaged rods, or rolled sheets. It has a low residual induction and, therefore, requires a relatively large area for a given flux. However, it has the highest intrinsic coercive force of any available permanent magnet and the ability to withstand extremely severe demagnetizing effects, such as in reverse current relays. It is also used as a moving element in instruments to measure strength of other permanent magnets. Pieces over $1\frac{1}{2}$-in. long are very difficult to magnetize.

Other Materials. Alloys of iron and 77 per cent platinum, cobalt and 77 per cent platinum, iron-platinum-rhodium, and iron with 93 per cent neodymium also exhibit permanent magnetic characteristics. They are principally of academic interest because their cost is very high. But they are characterized by very high coercive force from 1400 to 4000 oersteds, with correspondingly high external energies. Another group known as the *Heusler* alloys are made from certain combinations of manganese-copper, some with aluminum and tin additions. They do not have outstanding magnetic properties but are of interest to metallurgy and research because the constituents themselves are not ferromagnetic.

6.40 CONCLUSION

The various properties of resistors, conductors, contacts, electromagnet and permanent-magnet materials have been discussed in this chapter. Effects of operating and process conditions have been mentioned. The design of electrical equipment must be based on calculation or estimation of a number of these properties and conditions. Laboratory tests are helpful, but consideration must also be given to the manufacturing processes to be used, the degree of control under which these processes can be operated, and the effects of variations in the processes upon both the properties and the product components.

Review Questions

1. (*a*) Name three good metallic conductors of electricity and three which are relatively poor. (*b*) What nonmetallic conductors are important in engineering? (*c*) Name three uses for semiconductors.

2. Calculate the area in circular mils of a copper bus bar $\frac{3}{8}$ in. by 3 in. in cross section. What is its resistance at 68 F in a length of 45 ft?

3. The resistance, per conductor, of a transmission line is 9.61 ohms, measured when the average air temperature is 42 F. If the expected extremes are -20 F and 90 F, what are the maximum and minimum resistances per conductor of the line? Assume the conductor temperature is the same as that of the air. ($a = 0.00218$ per °F at 68 F.)

4. Explain "skin effect" and "proximity effect," and tell how they affect the resistance of a conductor.

5. What is meant by the term "superconductor"?

6. What three factors describe the conditions under which contacts are applied?

7. Name the two factors that affect contact resistance, and describe how the resistance decreases with each.

8. *A pair of copper contacts for operation under oil at 100 amp, and 440 volts, 3 phase, 60 cycles will malfunction if 10 g are lost from the pair. What number of operations may be expected?*

9. A pair of silver contacts for a household appliance must last for 25 years with 100 operations per day making 19 amp and breaking 5 amp at 60 cycles, 110 volts. How much contact volume should be provided?

10. List the six characteristics that are most often of importance in contact application.

11. How do diamagnetic, paramagnetic, and ferromagnetic materials react when exposed to a magnetic field?

12. (a) In English units, magnetizing force is expressed in amp-turns per in, and flux density in lines per sq in. What are the metric units for these quantities? (b) Write the equation which defines permeability. Are the units of the equation English, metric, or can either be used?

13. Sketch a magnetization curve and indicate an air line, the intrinsic flux, and the point of saturation.

14. Sketch a hysteresis loop, showing B_r and H_c. What is the significance of these quantities?

15. Laminations are usually stress-relief annealed after punching. What benefit does the relief of stress accomplish?

16. Core losses in silicon-magnet steels decrease with increasing silicon content. Why should the low-silicon steels be used at all?

17. Sketch hysteresis loops for (a) a transformer-core material, (b) a permanent-magnet material, and explain why each is adapted to its use.

18. Sketch a demagnetization curve, and from it construct the external-energy curve for that material.

19. In general, what is the purpose of heat treating a permanent magnet?

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7 IRON AND STEEL

7.1 INTRODUCTION

This period in which we are living has been appropriately called the "Iron Age." No event in the history of civilization equals in importance the development of the art of producing iron and steel. There is evidence that a few iron tools were in use in India, China, and Egypt over 4000 years ago. These early implements were probably produced by subjecting lumps of iron ore to long exposure to an ordinary campfire; and then beating the extracted metallic iron into the desired shapes, forming a material resembling wrought iron.

Iron was used but little, however, until the invention of the blast furnace made large quantities of the metal available. This was followed by the invention of large-scale refining methods such as the Bessemer and open-hearth processes, which gave to mankind its most useful material, steel. Today, the production of iron and steel is about 15 times that of all other metals combined.

7.2 PRODUCTION OF IRON AND STEEL

Iron is the name given to pure ferrite, Fe, as well as to fused mixtures of this ferrite with large amounts (above 1.7 per cent) of carbon, these mixtures being known as *pig iron* and *cast iron*. Intermediate between the pure iron and cast iron is *steel,* in which none of the carbon is in elemental form. Most of the carbon in steel is combined in the intermetallic compound, iron carbide.

Pig iron is produced from iron ore in the blast furnace. It is the basic raw material from which all cast iron, wrought iron, and steel are made. Cast iron is obtained by slightly purifying the pig iron in a "cupola" or other furnace in which the composition of the iron can be varied. Wrought iron and steel are obtained by considerable furnace purification of the pig iron.

7.3   THE BLAST FURNACE

The blast furnace is used to obtain pig iron by the chemical reduction, called *smelting,* of iron ore.   It was invented in Germany about 1400.   Successive improvements have been made over the years, and today the modern blast furnace stands from 75 to 110 ft high and produces up to 1000 tons of iron per day.   It operates continuously and need not be shut down for repairs oftener than once every 5 to 7 years.

The principal parts of the furnace are shown in Fig. 7.1.   The
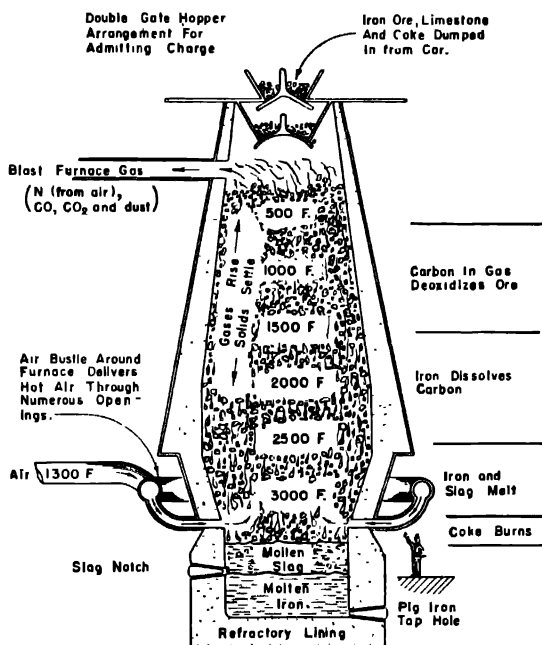
FIG. 7.1.   Elementary cross section of blast furnace ready for tapping.   Slag notch will be opened and slag drawn off, then iron will be drawn from the tap-hole.   The supports and the cooling systems have been omitted.

charge is put in at the top.   The molten iron and impurities are drawn off separately at the bottom as they accumulate.   The hoppers at the top receive iron ore, limestone, and coke.   This charge is admitted to the furnace during cyclic opening of the gates.   The ore contains iron in the form of Fe_2O_3, in hematite ore, or Fe_3O_4, in magnetite ore.   The limestone helps reduce these iron oxides and unites with the ash of the coke and the impurities in the ore to form *slag,* which melts near the bottom of the furnace.   The coke also helps

reduce the iron oxides, furnishes carbon to saturate the iron, and ultimately burns in the lower part of the furnace, supplying heat to melt the iron and slag. This slag floats on top of the molten iron, like cream on milk, and is removed through the slag notch. A large volume of hot air is blown in at the bottom of the furnace to promote combustion of the coke and to help carry the gases upward. The temperatures are approximately as shown, although production values are controlled to suit the nature of the ore being smelted.

7.4 CHEMICAL REDUCTION IN THE BLAST FURNACE

The more important materials present in the blast furnace charge, except for carbon, are shown in Fig. 7.2. The oxides are arranged in
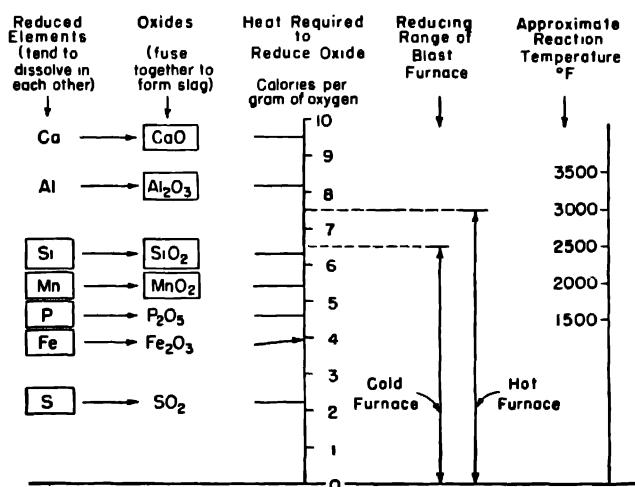
FIG. 7.2. Heats of formation of oxides present in the blast furnace and approximate reducing temperatures. Squares indicate substances that are normally present in the lower region of the blast furnace.

order of increasing stability; that is, the higher an oxide occurs on the scale the more difficult it is to reduce, or deoxidize, and the more easily the corresponding metallic element is oxidized. Lime (CaO) is therefore the most "stable" oxide on the scale; whereas sulfur dioxide (SO_2) is relatively unstable, only a small amount of heat being required to reduce it to its elements, sulfur and oxygen. The elements appearing above iron will take oxygen from iron oxide. Silicon, for instance, is such a *reducing agent* (also called deoxidizer) for iron.

Carbon is not shown in Fig. 7.2 because its position changes, de-

pending upon the temperature. At low temperatures carbon dioxide (CO_2) is below Fe_2O_3 in the scale. But at high temperatures it is above P_2O_5. The relative positions of the various oxides in Fig. 7.2 determine the reaction temperature required in the blast furnace. In general, the more heat the reaction requires, the hotter the material must be in order to maintain good reaction speed.

The blast furnace operator makes use of two very important characteristics of the materials shown in Fig. 7.2. First, the oxides collect together to form a slag and the pure, reduced elements dissolve in each other. Second, the molten slag does not mix with the molten metal but, being lighter, floats on top.

It would be ideal if the iron oxide could be reduced to pure iron and all of the other impurities left in the form of oxides in the floating slag. The heat of formation of the various oxides, however, prevents this ideal reduction procedure. This can be explained as follows: Consider a blast-furnace charge of iron ore and coke only, no limestone. The ore and coke contain impurities in the form of S, SO_2, P_2O_5, MnO_2, SiO_2, and Al_2O_3. If the temperature at a certain point in the blast furnace were just high enough to drive the oxygen out of the iron ore and leave pure Fe, P_2O_5 and other higher oxides would remain in the slag. The iron would dissolve sulfur, because sulfur would also be entirely deoxidized at this temperature. This represents the situation about halfway down in the ordinary blast furnace. At this stage the iron is still solid; its reduction has taken place entirely in the solid state. As the furnace charge settles farther toward the bottom it becomes hotter and hotter. Phosphorus is reduced and dissolves in the iron, and then Mn and Si follow. Therefore, if iron ore and coke were the only materials used in the charge, the iron, by the time it reached the liquid state in the bottom of the furnace, would contain almost all the S and P and a considerable portion of the C, Mn, and Si. A molten slag of Al_2O_3 and some SiO_2 and MnO would also appear at the bottom of the furnace, floating on top of the molten iron.

The amount of Si and Mn in pig iron can be minimized by operating the furnace "cold," i.e., by decreasing the reducing intensity of the furnace. The minimum temperature, however, is the melting point of iron. At this temperature, phosphorus is still reduced and the pig iron contains *all* the phosphorus that entered the furnace.

A large amount of sulfur also enters the furnace in the coke, and all of it would appear in the pig iron if limestone ($CaCO_3$) were not added to the charge. Part way down the furnace, the limestone liber-
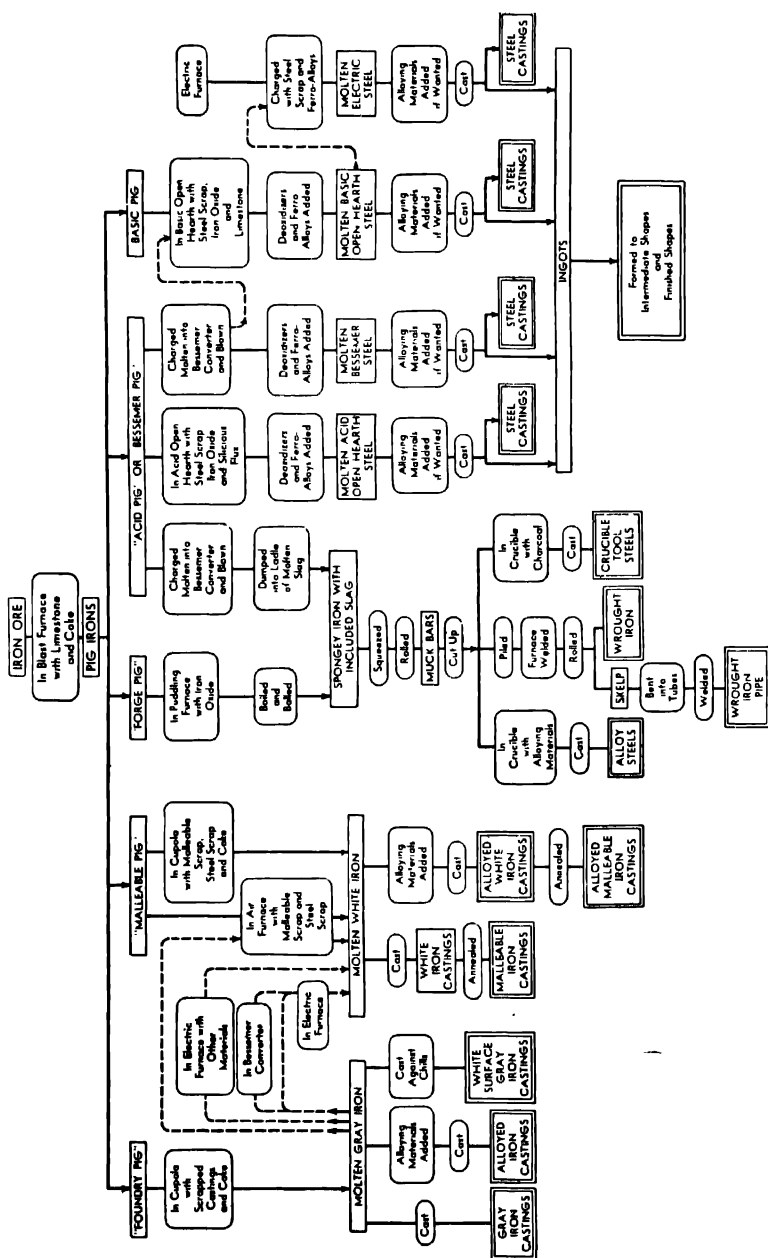
Fig. 7.3. Diagram indicating typical foundry and mill applications for different grades of pig iron. Finished products are shown in double outline.

ates CO_2 and becomes lime (CaO), which is a very stable oxide. Some of the lime reduces the sulfur to CaS, which passes off in the slag. The lime accomplishes the further purpose of forming a free-flowing slag, which melts and drips rapidly through the hot lower part of the furnace, giving its collected oxides very small chance to be reduced and join the iron.

Normally, then, the pig iron tapped from the blast furnace will be low in oxides and sulfur, but its phosphorus content will be the same as that of the ore. Three to four per cent carbon from the fuel is dissolved in the iron. The remainder of the carbon goes off as a gaseous oxide.

7.5   PIG IRON

Pig iron is weak and brittle and is not used for structural purposes. Ordinarily, it is poured into large ladles and taken to a cupola or to an air furnace for making cast iron, or to the refining furnaces for making steel. If it cannot be used immediately, it is cast into blocks or *pigs*, which may be remelted later. The different ores and various blast-furnace procedures produce many grades of pig iron, each one with a special use in the foundry or the steel mill (see chart, Fig. 7.3). The compositions of various pig irons, and those of the products made from each, are shown graphically in Fig. 7.4.

7.6   CAST IRON

Cast iron is used in industry because of its low cost, good casting characteristics, high compressive strength, wear resistance, and good damping qualities. The principal types are: gray, white, malleable, ductile (nodular), and various alloy irons.

When cast iron solidifies, the last liquid to freeze is of the eutectic composition (4.3 C). If no other alloying element is present, the quantity of carbon must be at least 1.7 per cent for the eutectic transformation to occur (see Fig. 7.5). If the percentage is lower, there will be no final solidification of eutectic liquid, and the solid will not be cast iron. Impurities and alloys, however, change this value considerably; for instance, 2 per cent silicon lowers the possible carbon limit from 1.7 to 1.1 per cent.

7.7   GRAY CAST IRON

Twelve to 15 million tons of cast iron are produced in the United States each year. Of this total, gray cast iron comprises 85 per cent. It is made from low quality *foundry pig* which is charged (along with

scrapped castings and coke) into a cupola. The cupola is similar to a small blast furnace, and is the best place to melt scrapped castings, therefore salvaged cast scrap is used to control the alloying elements in the finished cast iron.
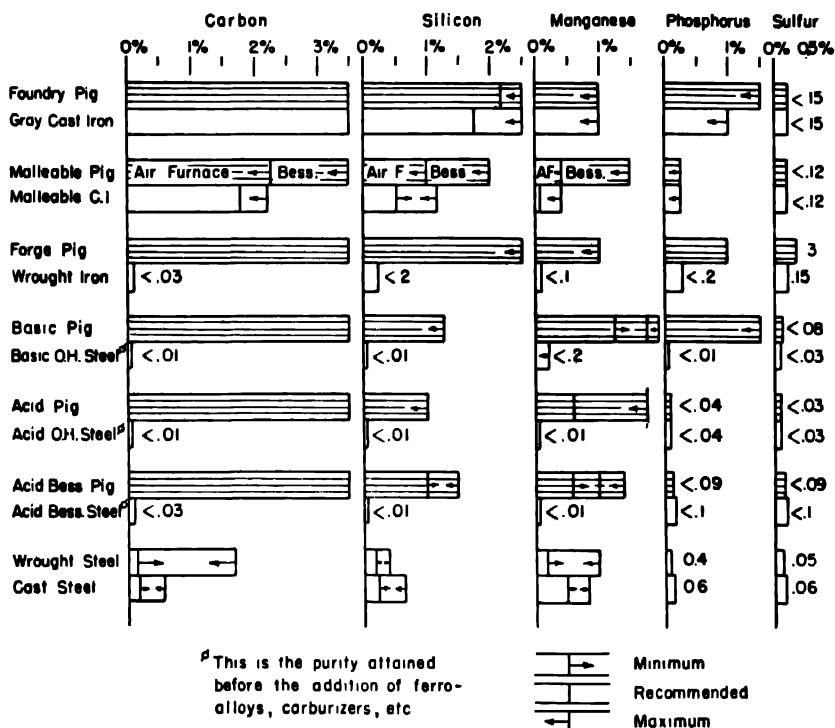
FIG. 7.4. Compositions of various pig irons and the cast irons and steels derived from them. Shaded bars represent pig irons. Unshaded bars represent refined product.

The photomicrograph, Fig. 7.6, shows that much of the carbon in gray iron is in the graphitic form. When this iron is fractured, the exposed graphite gives the break a gray appearance, hence the name. Although it is possible to produce this iron with all the carbon as free graphite flakes, this is not always desirable. In most castings, up to 0.8 per cent of the carbon is in the form of iron carbide, Fe_3C, and the balance, 2 to 4 per cent, is in the form of graphite. The eutectoid percentage of this carbide appears in lamellar pearlite. Any excess carbide appears as free massive grains.

Thus, a complete series of gray cast irons (see Table 7.1) is possible, ranging from those with all the carbon in graphitic form to those with a good share of the carbon in combined form. Since the carbides
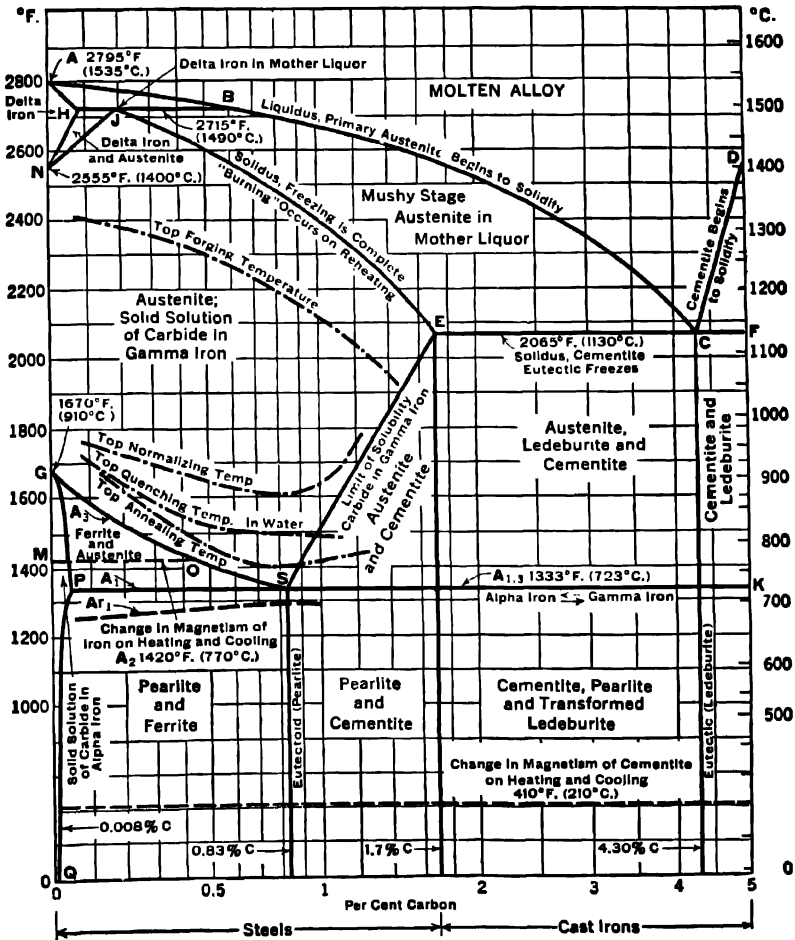
FIG. 7.5. Equilibrium diagram for the iron-carbon alloy system.

harden and strengthen the iron, the variation in properties is very great. Completely graphitic gray iron is a soft, readily machinable metal insensitive to notches, and high in damping capacity and compressive strength. Tensile strength, ductility, and impact strength are much inferior to steel, however, and there is also an absence of

Table 7.1   Properties of Typical Gray Cast Irons

Property	ASTM Class					
	20	25	30	35	40	
Tensile strength, psi	20,000	25,000	30,000	35,000	40,000	45,000
Compressive strength, psi	80,000	90,000	100,000	110,000	125,000	135,000
Hardness (Brinell)	110	140	170	200	230	265
Permanent set, psi	5,000	7,000	9,000	11,000	13,000	15,000
Endurance limit, psi	8–10,000	10–12,000	12–15,000	14–16,000	16–20,000	18 22,000
Mod. of elasticity, psi	11,000,000	12,000,000	13,000,000	14,000,000	15,000,000	16 000 000
Torsion modulus, psi	4,000,000	4,500,000	5,000,000	5,500,000	6,000,000	6,500,000
Toughness (Izod impact)	.	Less than 1	.	. . •	. .	
Creep, 0.1%/1000 hr						
840 F	.	.	8,000	8,000	. .	
1000 F	. .	. .	0	0	.	.
Machinability	Excellent	Excellent	Excellent	Excellent	Good	Fair
Wear resistance	Good	Good	Good to exc.	Excellent	Excellent	Good to exc.
Corrosion resistance	Fair	Fair	Fair	Fair	Fair	Fair
Vibration damping capacity	Excellent	Excellent	Excellent	Excellent	Good to exc.	Good
Specific gravity	7.0	7 0	7.1	7.2	7 3	7 4
Melting point, °F		2150–2300				
Thermal exp. $\times 10^{-6}$/°F	6 7	6.7	6 7	6.7	6 7	6 7
Thermal conductivity, cgs units	0.11	0.11	0 11	0.11	0 11	0 11
Electrical res., microhm-cm	80–100	80–100	80–100	80–100	80–100	80–100
Magnetic permeability (gausses with H at 100)	9000	9000	9000	9000	9000	9000

well-defined yield limit and modulus of elasticity, which are limitations for some uses. Irons with a high proportion of the carbon occurring as carbide are hard, brittle, unmachinable, and have good wear resistance. A close-grained iron containing graphite and pearlite is generally the strongest, toughest, and best finishing type of cast iron. Medium gray irons contain some ferrite, with graphite and pearlite resulting in less strength and poorer finish. Open gray iron has low strength and machines soft but is best of these grades in wear resistance.

The relative amount of free and combined carbon is controlled by variations in composition, melting practice, and casting practice. The most potent single factor is the presence of silicon, which promotes the decomposition of cementite into free iron and graphite. Another important variable is the cooling rate of the iron in the mold. Slow cooling aids the formation of graphite; rapid cooling aids the formation of cementite. Iron, which would be gray throughout if cast in sand, may be given a "white" surface by casting it against

chills, which cool the surface rapidly. Ordinarily, it is desired that the amount of combined carbon in gray cast iron be less than the eutectoid percentage. For this reason, the silicon content is kept up to about 2 per cent and the metal is cooled without chilling.

Sulfur has the effect opposite from silicon; it stabilizes the carbide and thereby tends to "chill" the iron. This action is prevented if manganese is present in sufficient amounts ($2 \times S$ per cent + 0.2 per cent) to combine with all of the sulfur to form manganese sulfide. Phosphorus in cast iron occurs almost entirely combined with iron and carbon to form an eutectic called steadite. It forms an embrittling network but does not materially decrease the strength.

7.8 WHITE, OR CHILLED, CAST IRON

White iron has a characteristic white color because it contains no graphite. All of the carbon is in the form of cementite, either free or in lamellar pearlite (see Fig. 7.7). White iron may be produced by two methods: (*a*)

FIG. 7 6. Photomicrograph of gray cast iron, $\times 1000$. White areas are ferrite; mottled areas pearlite; and black areas graphite.

by casting gray iron against chills to cool it rapidly and give it a white surface layer, or (*b*) by adjustment of composition through keeping carbon and silicon low so there is no free carbon throughout.

This adjustment is made in an air furnace where low-phosphorus pig iron and steel scrap are melted together. The air furnace heats the charge from above in a manner similar to the open hearth, and is used because the entire charge can be dumped in, heated, and carefully controlled. Cupola furnaces alone are sometimes used for making low-quality white castings, but better castings can be made by "duplexing" or "triplexing" processes which combine the cupola, air furnace, Bessemer converter, and/or electric furnace (see Fig. 7.3).

White cast iron is a very hard, brittle, wear-resistant material. If the silicon is kept below 1 per cent and the carbon is adjusted to about 2 per cent in common cast iron, a white iron of about 400 Brinell will usually result.

In amounts greater than 3 per cent, chromium usually prevents the formation of graphite. The resultant iron not only has the common properties of other white irons, but also has better high-temperature strength, grain-growth resistance, and corrosion resistance.

Small additions of nickel and chromium, such as 4.5 per cent Ni and 1.5 per cent Cr, double the strength and significantly increase the toughness of white castings. They are used when an extremely hard (700 Brinell), tough, and strong material is desired.

7.9 MALLEABLE CAST IRON

Approximately 1 million tons of the white iron castings made in the United States are converted into malleable iron castings each year. This is done by annealing to dissociate the cementite. In Europe, the castings are packed in an oxidizing material, and the malleablized castings are known as "white heart," through removal of some carbon. The practice in the United States is to anneal castings packed in an inert material, such as ferrous silicate scale or slag. These malleablized castings, known as "black heart," consist almost entirely of graphite and ferrite. The carbon, previously in the form of cementite (Fig. 7.7), agglomerates and forms "rosettes" of pure temper carbon scattered in a matrix of almost pure iron (Fig. 7.8). The annealing process consists in heating slowly to 1600 F, holding at temperature for 25 to 60 hr, depending on size, and slow cooling at 10 F per hr.

Cupola white iron for malleablizing (ASTM-A197-39) results in higher bursting strength under pressure but lower strength than air-furnace, open-hearth, electric-furnace, or duplexed irons. The cupola product is therefore often used for valves and pipe fittings. The higher-grade products are usually ASTM-A47-33, grades 32510 and 35018. These grades have, for ½-in. sections, tensile strength over 50,000 psi, yield strength over 32,000 psi, 2 in. elongation of 10 per cent or more, 7–9 ft-lb Izod impact resistance, modulus of elasticity of 25 million psi, an endurance ratio of 0.5, good moldability, machinability equal to gray irons, poor wear resistance, and sensitivity to notches. Thus, they are more like low-carbon steels than cast irons. Their cost is usually higher than gray irons because of the time re-

quired for annealing, but they are lower in cost than the softer steels.

Both short-cycle annealing, which interrupts graphitization, and addition of elements that retard graphitization result in malleable irons containing both temper carbon and 0.2 to 0.6 per cent carbon combined as pearlite or sorbite. These are called *pearlitic malleable irons*. They possess higher strength and wear resistance than grade

Fig. 7.7. Photomicrograph of white cast iron ×250. White areas are cementite (Fe_3C), and mottled areas are pearlite.

Fig. 7.8 Photomicrograph of malleable cast iron, ×125. Black "rosettes" are temper carbon in a matrix of almost pure iron (white).

35018, at some sacrifice in elongation and machinability. Grades of this type are often sold under special trade names.

7.10 DUCTILE CAST IRON

A development of importance to the foundry field has been the successful production of ductile iron. Small additions of magnesium (or more expensive cerium) at the ladle renders the graphite content nodular, or spheroidal, in form, and well dispersed throughout the material. The resulting structure possesses properties more like a cast steel than like the other grades of cast iron, yet production follows gray-iron practice.

Ductile iron is not a single material, but is, instead, a family of materials. Its structure may be modified by alloys or heat treatment,

as in steel, to produce austenitic, acicular, martensitic, pearlitic, and ferritic structures. Interest to date has centered on the pearlitic-ferritic grades, the four principal types being those listed in Table 7.2.

Table 7.2 Representative Mechanical Properties of Commercial Heats of Ductile Iron, 1-In. Bars *

Grade	Tensile Strength, psi	Yield Strength, psi	Elongation, per cent	Bhn	Usual Condition	Remarks
90-65-02	95/105,000	70/75,000	2 5/5 5	225/265	As cast	Good wear resistance.
80-60-05	85/95,000	65/70,000	5.5/10 0	195/225	As cast	Combined strength and toughness.
60-45-15	65/75,000	30/60,000	17.0/23.0	140/180	Annealed	Max toughness and optimum machinability.
80-60-00	85/95,000	65/75,000	1.0/3.0	230/290	As cast	More Mn and P, high strength and stiffness; low shock resistance.

* Reprinted from "The Industrial Status of Ductile Iron," *Mech. Eng.*, February 1951, pp. 101–108, with permission.

Compositions currently used range as follows: 3.2 to 4.2 per cent C; 1.0 to 4.0 per cent Si; 0.1 to 0.8 per cent Mn; 0.1 per cent P; 0 to 3.5 per cent Ni; and 0.05 to 0.10 per cent Mg. The magnesium controls the graphite form but has little influence on the matrix structure. Nickel and manganese add strength at the sacrifice of ductility. Less manganese is used than is in typical gray irons, because sulfur is very low in ductile irons. Silicon is used as an alloying element since it has no effect on size and distribution of the carbon content.

Advantages of this iron are high fluidity, excellent castability, high strength, high toughness, excellent wear resistance, pressure tightness, weldability, higher machinability than gray iron, and an elastic modulus of 25 million psi. In 1952 it was being produced at a rate of 20,000 tons per year. The attractive properties give promise that production may reach 2 to 5 million tons per year, making this material the third most used behind steel and gray cast iron.

7.11 ALLOYED CAST IRON

Many foundries have attempted unsuccessfully to produce alloyed cast irons in cupola furnaces, but the difficulties met in attempting to add alloying elements in the cupola are almost insurmountable. The alloying compounds may be added to the cupola charge, but very often do not melt evenly. The castings then have nonuniform composition. If the alloys are added to the pouring ladle after the molten

iron is drawn from the furnace, the ladle iron must be very hot to overcome the chilling effect of the alloy, and even then the mixture is apt to be nonuniform.

Many of the disadvantages of the cupola are overcome by use of the "batch process" in an air furnace or an electric furnace. In these furnaces it is possible to control the composition, since the charge is melted all at once, instead of continuously as in the cupola. Probably about 15 or 20 per cent of the cast iron being produced now is alloyed, and many foundries make a specialty of this type of casting.

The principal reasons for alloying cast iron are to increase its strength and to improve its corrosion resistance. Since alloying is a process requiring special melting practice, alloys are added to good irons to make them better, never to poor irons to make them good.

Nickel in amounts up to 5 per cent is added to cast iron primarily for its effect on machinability; it may be made either to increase the hardness and strength without appreciably decreasing the machinability, or to improve machinability without decreasing hardness and strength. The nickel also promotes corrosion resistance and uniformity of properties throughout variations in casting thickness.

Chromium, up to 3 per cent, has the opposite effect of silicon and nickel; it inhibits the formation of graphite, promotes the formation of carbides, and, in addition, increases the corrosion resistance. Higher percentages of chromium therefore harden the iron by increasing the percentage of combined carbon.

Nickel and chromium added in 3-to-1 ratio to 4 per cent total have their graphite- and carbide-forming tendencies neutralize each other, and this results in iron with improved grain refinement, hardness, and strength, and with no impairment of the machinability.

Molybdenum, up to 1.5 per cent, is the most effective alloying element for improving strength; wear resistance is also increased, with a consequent decrease in machinability. Molybdenum improves the uniformity of structure in heavy sections by slowing up graphitization and retarding the critical transformation.

Vanadium, up to 0.5 per cent, is a very powerful carbide former and increases the strength and hardness of cast iron considerably, even in the small amount used.

Properties typical of some alloy gray irons are listed in Table 7.3. The lower grades are used for such parts as cylinders, brake drums, and sprockets. Higher grades are used where high impact, wear, and fatigue resistance are required as in dies, machine-tool castings, and critical machinery components.

Table 7.3   Properties Typical of Some Alloy Gray Cast Irons

Property	ASTM Class					
	30	35	40		50	60
Tensile strength, psi	30,000	35,000	40,000	45,000	50,000	60,000
Compressive strength, psi	100,000	110,000	125,000	135,000	150,000	175,000
Hardness (Brinell)	170	190	210	230	250	275
Permanent set, psi	9,000	11,000	13,000	15,000	17,000	19,000
Endurance limit, psi	15,000	17,000	20,000	22,000	25,000	30,000
Mod. of elasticity, psi	14,000,000	15,000,000	16,000,000	17,000,000	18,000,000	20,000,000
Torsion modulus, psi	5,500,000	6,000,000	6,500,000	7,000,000	8,000,000	9,000,000
Toughness (Izod impact)	.	..	Less than 1	..	Up to 2	Up to 2
Creep, 0.1%/1000 hr						
840 F	.	9500				
1000 F	..	0				
Machinability	Excellent	Excellent	Excellent	Excellent	Good to exc	Good to exc.
Wear resistance	Excellent	Excellent	Excellent	Excellent	Good to exc	Good to exc.
Corrosion resistance	Fair to good	Fair to good	Fair to good	Fair to good	Fair to good	Fair to good
Vibration damping capacity	Excellent	Excellent	Excellent	Excellent	Good to exc	Good to exc
Specific gravity	7 1	7.1	7.2	7 2	7.3	7.3
Melting point, °F			2150–2300			
Thermal exp. $\times$ 10^{-6}/°F	6 7	6.7	6 7	6.7	6.7	6.7
Thermal conductivity, cgs units	0.11	0.12	0.12	0.12	0.12	0.12
Electrical res., microhm-cm	80–100	80–100	80–100	80–100	80–100	80–100
Magnetic permeability, gausses with H at 100	9000	9000	9000	10,000	10,000	10,000

Austenitic Gray Cast Iron. If iron is alloyed in such a way that the critical transformation temperature is lowered below room temperature, the iron will remain in the form of austenite (γ-iron) rather than transforming to ferrite (α-iron) as it cools to room temperature.

Austenitic cast iron, which bears the same relationship to ferritic cast iron that stainless steel bears to carbon steel, has excellent corrosion and erosion resistance and good wearing qualities, strength, and hardness.

Nickel, 10 to 20 per cent, is the only alloying element known that alone causes iron to remain in austenitic form (at room temperature) without causing its carbide content to increase. Martensitic nickel irons are also available.

Inoculated Irons. High-strength irons of such composition that they would ordinarily be white as cast are often *inoculated* in the ladle with a silicon compound to cause graphitization. Typical agents used are ferrosilicon, calcium silicide, Si-Mn-Zr, or Ca-Mn-Si in crushed form. Trade names are used to designate the inoculated products, and the practice may be employed with plain carbon or

alloy cast irons. The resulting product is a uniformly dense and machinable casting which might have been "white" in thin sections and soft and porous in heavy sections.

7.12 HEAT TREATMENT OF CAST IRON

The heat treatments used on cast irons, and their purposes, are as follows:

Stress Relief. This treatment is accomplished by heating to 800–1100 F, holding at temperature for 30 min to 5 hr, and cooling slowly in a furnace. Along with the relief of internal stress, only slight decrease in hardness or strength occurs at room temperature.

Annealing. Iron castings are sometimes softened to facilitate machining, and this is accomplished by annealing. The material is generally heated to 1400–1500 F, and longer time is required than with steel because of the extra carbon to be absorbed and of the retarding effect of silicon. Higher temperatures up to 1800 F are needed with the highly alloyed irons. The annealing operation generally increases the free carbon and decreases the strength, although the strength reduction is less for the alloyed irons.

Hardening. The alloyed irons are often quenched from above the transformation temperature (1500–1600 F) and then tempered to improve their hardness and resistance to wear. About 0.5 to 0.8 combined carbon is obtained in a pearlitic or sorbitic structure. Quenching usually is performed in oil, although water and air quenching are used for some grades.

The soft gray irons can develop a martensitic structure when quenched, but these irons are not commonly used when hardening is desired. They require a long time at austenitizing temperature to absorb the free graphite, especially if silicon content is high. Austempering, a patented process of quenching and holding at an intermediate temperature, is sometimes used for improving strength and wear resistance of gray iron. The temperature of the salt bath is maintained at 500 to 550 F, and the casting is held in the bath for $\frac{1}{4}$ to 1 hr, depending on size and composition.

Castings of eutectoid-percentage combined carbon may be hardened satisfactorily in localized areas by flame and induction methods.

Alloyed irons of special composition can be nitrided to obtain high surface hardness and wear resistance. The process is performed at 950 to 1100 F in contact with anhydrous ammonia gas, and takes from 20 to 90 hr, depending on the size and depth of hardening desired.

7.13 OTHER PROPERTIES OF CAST IRONS

The metallurgy of the cast irons and their mechanical properties have been reviewed in the foregoing. Some other properties of these materials as a class are:

Machinability. The cast irons range in machinability from very good to the most unmachinable of the ferrous alloys, whether their rating be based on tool life, finish, or power required. Annealed permanent-mold iron is the most easily machined because it contains no combined carbon, has finely divided and dispersed graphite flakes, and is free of burned-in sand at the surface. Ductile iron also rates high. In increasing order of difficulty in machining are pearlitic-ferritic irons, pearlitic irons, mottled iron with pearlite and massive cementite, and white iron. The latter is especially difficult to machine because its structure is largely massive carbide, almost unbroken, with free graphite flakes. Burned-in sand from the casting process may condemn an otherwise machinable iron, if the machining cuts are not deep enough to get below the sand-included surface.

Weldability. The weldability of cast irons of all types is considered poor. Special processes are required, making it economical only to weld components as a method of salvage or repair. Forge and submerged-melt welding cannot be used. Gas and arc welding are satisfactory, particularly for sections over $\frac{1}{4}$ in. thick with special rods, if the casting is heated to a red heat before welding and cooled slowly to room temperature thereafter. Bronze welding is satisfactory both for gray irons and for white irons before malleablizing and without preheat, if temperatures of 1500–1600 F are obtained in the process. This method is probably the most used for repair.

Corrosion Resistance. This property has been discussed in Chapter 5. Though not immune to rust, the irons form rust slowly and penetration is quite slow in comparison with the low alloy steels. High-silicon grades are suited to acid environment as are the high-chromium grades, but both, as well as the unalloyed grades, have poor resistance to caustics. High-nickel austenitic irons, like ni-resist and Causul metal, are resistant to some acids, excepting nitric, and to stress corrosion in hot, strong caustics if stresses are low.

High Temperature. For pressure vessels a practical limit for gray cast iron service is 650 F. Mechanical properties for other applications are suitable to 800 F, with marked creep resistance to 600 F, and good creep and fatigue resistance to 800 F. Repeated heating of gray cast iron to temperatures above 800 F causes grain growth, distortion, and brittleness. Excessive scaling occurs above 1100 F.

Lower carbon, lower silicon, and more chromium increase the permissible temperatures. High-silicon irons, high-chrome irons, and the austenitic nickel cast irons resist grain growth to still higher temperatures.

Magnetic and Electrical Properties. These properties are discussed in Chapter 6.

7.14 WROUGHT-IRON PRODUCTION

Wrought iron was the first tough, ductile material used in structural work, but it is used very little today. This is because many steels are superior in almost every way to wrought iron, and are much less
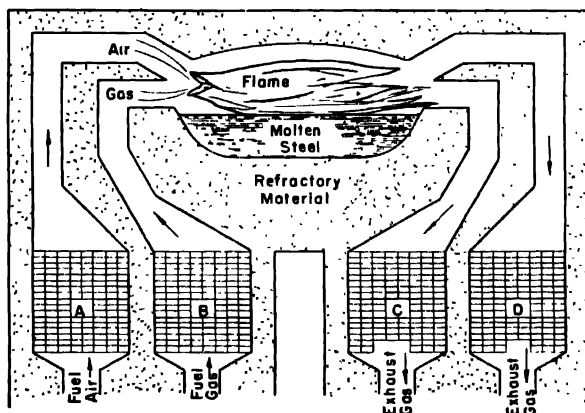
FIG 7.9. Elementary cross section of the open-hearth furnace. *A, B, C,* and *D* are checkerworks for storing heat. When the flame is in the direction shown, *C* and *D* are being heated by the burned gases. Every 15 mm the direction is reversed; i e , air and gas will enter through *C* and *D*, which are hot; the flame will burn from the right side, and *A* and *B* will be heated by the burned gases. As time goes on, the system becomes hotter and the flame gradually grows more intense. This is known as the regenerative principle.

expensive. Wrought iron remains superior for some applications, however, where corrosion and severe fatiguing conditions exist. A good grade of pig iron called *forge pig,* containing less than 1.75 per cent silicon and less than 1 per cent phosphorus, is the material used (see Figs. 7.3 and 7.4) and is refined into wrought iron either by "puddling" or by the Aston or Byers process.

Puddling Process. The puddling process was invented about 1780. It consists in placing a charge of forge pig in a saucer-shaped hearth. Melting is caused by a flame from above, similar to that employed in the open-hearth furnace (see Fig. 7.9). As the iron melts, iron oxide

is added to oxidize the Mn and Si impurities and to start the forma-
tion of a slag. When this is completed, the carbon begins to oxidize
and burns from the surface of the metal. As the carbon is elimi-
nated, the melting point of the mix is raised and solid iron starts to
precipitate. The puddler starts stirring the mix, thus agglomerating
the precipitated iron into a ball, which he removes, dripping with slag,
from the furnace. The ball is taken to a *squeezer*, where much of the slag is squeezed out. Then it is rolled into a bar (called a *muck bar*), thereby removing more slag. This muck bar is cut into short lengths and is the finished product, wrought iron. It is very pure, except for 1 to 2 per cent slag in the form of streamers scattered throughout the ferrite matrix (see Fig. 7.10). If the wrought iron is to be used for other than crucible steel, several muck bars are laid side by side, furnace welded, and rerolled several times. This refines the grain, eliminates a little more slag, and provides larger billets for struc-tural use.

Fig 7 10. Photomicrograph of wrought iron, ×100. Black areas are slag inclusions in nearly pure iron (white).

Because a large amount of hand labor is required in the puddling
process, it is expensive and is little used today.

Aston or Byers Process. Many of the difficulties encountered in
the production of wrought iron in the puddling furnace were overcome
in 1930, when Aston and Byers developed a method requiring no
puddling. In their process, the pig iron is purified in a Bessemer con-
verter (see Fig. 7.11) and then dumped into a ladle of molten slag.
The temperature of the slag is several hundred degrees lower than
that of the iron, and a violent reaction takes place, mixing the slag
through the iron. The resulting mass resembles the puddler's "puddle
ball," and subsequent squeezing, rolling, piling, furnace welding, and
rerolling yield a wrought iron that is very similar to that produced
in the puddling process. The iron produced by the Aston process is

more uniform, never containing large slag inclusions or streaks of pure carbon such as sometimes appear in puddled iron.

A. Tilted for Charging   B Blowing
                                    Air
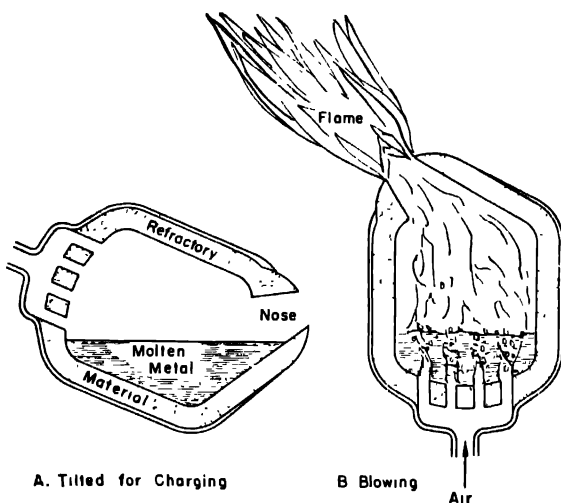
FIG. 7.11. Elementary cross section of the Bessemer converter. Molten pig from the blast furnace is charged in the nose. Air is turned on and the converter is tilted upright as in *B*. Blowing continues for 10 or 12 min. The converter is then tilted in the opposite direction and emptied.

7.15 PROPERTIES OF WROUGHT IRON

The mechanical properties of wrought iron are not high in comparison with structural steel. Tensile strength ($\frac{1}{2}$ in. round) is 42–52,000 psi, yield point 26–35,000 psi, elongation (8 in.) 25–40 per cent, reduction in area 40–55 per cent, reversed bend endurance 19–23,000 psi, axial endurance 11–16,000 psi, and Charpy impact 5 ft-lb transverse to 18 ft-lb longitudinal. The tensile strength properties drop off at 700 F and reach half their room-temperature value at about 900 F.

Bend tests are often used as a quality check. High-quality bars will bend flat on themselves at 17–1800 F, whereas lower-quality bars can be bent on a pin diameter of their thickness at 1500 F. Similar tests are also made in the cold condition.

Nickel-alloy wrought iron, with $3\frac{1}{4}$ to $3\frac{1}{2}$ per cent Ni, has improved strength. Typical values are 55–60,000 psi tensile strength, 45–50,000 psi yield point, 8 in. elongation 25–30 per cent, and 35–45 per cent reduction in area.

Wrought irons may be carburized by much the same process as for

mild steel (C1010). These irons are also easily welded by forge, gas, and arc methods. The resistance to progressive corrosion of the usual wrought iron is considered high, probably because the slag content aids formation of a tight oxide rust on the surface. High impurity wrought irons, especially those known as "common iron," have more limited resistance to corrosion.

7.16 COMMERCIALLY PURE IRON

Commercially pure iron is sometimes used for its good ductility and resistance to corrosion. It has been produced by many methods, but few have been commercially exploited. One process which has been successful takes place in the basic open-hearth furnace. The composition of the charge and furnace lining are carefully chosen, and the process is longer and more sensitive to control than is open-hearth steelmaking. The resulting iron is known as *ingot iron* (or by its trade name, *Armco iron*) and contains about 0.2 per cent total impurities. It is used in wire fencing, culverts, flumes, gutters, troughs, home furnaces, or for other applications that require moderate resistance to rusting.

A commercially pure iron is also made by electrolytic deposition. Since its total impurities may be considerably less than 0.1 per cent, it is very ductile and can be rolled or hammered, like gold, to very thin sheets. It is expensive and the commercial production is small.

7.17 STEEL PRODUCTION

Steel can be manufactured in great quantity at small expense and with many varieties of desirable physical properties. Many parts formerly made of cast or wrought iron are now either cast or fabricated from steel.

Steel production capacity in the United States during 1950, as reported by the American Iron and Steel Institute, was as follows. It is estimated that production in the United States was 96 per cent of capacity in 1950, or 96,500,000 tons, almost half the world production.

	Net Tons
Open-hearth steel (about 95 per cent basic open hearth)	87,858,990
Bessemer steel (acid)	5,621,000
Electric-furnace and crucible steel	7,083,490
Total	**100,563,500**

Open-Hearth Processes. In 1856 Siemens patented the open-hearth furnace, which was destined to become the largest producer of steel. The outstanding feature of this furnace is the intense heat obtainable by its regenerative process (see Fig. 7.9). The flame burns above a shallow vessel containing the charge of pig iron, steel scrap, iron ore, and flux. As the charge melts, the flux forms a slag which is raked off into slag pockets at the side of the furnace. Figure 7.4 indicates graphically the purification that takes place in the furnace. Recarburizers and ferroalloys (high-alloy-content iron alloys) are added after refining to bring the steel to the desired composition, since the carbon, silicon, and manganese contents may be lower than desired. This apparently wasteful procedure of eliminating the impurities and then adding them again in the desired amounts is, in reality, more efficient than trying to decrease them to just the right amounts.

At the high temperatures encountered in the furnace, the furnace lining becomes chemically active. Silica becomes an acid, while the other common lining materials, calcium and magnesium oxides, become bases. The slag is also chemically active, but its acidity or alkalinity can be controlled by selection of flux. If the lining is basic, the flux must also be basic, or the slag would destroy the lining; the converse is, of course, true. The basic slag of a *basic open-hearth* furnace will remove most of the silicon, manganese, and phosphorus in the iron, as well as some of the sulfur; but the *acid open hearth* will remove only the silicon and manganese (phosphorus and sulfur remain). The basic furnace can refine dirtier pig iron and is by far the more popular, even though the lining is more expensive than the acid lining.

Each heat (complete refining cycle) requires about 10 hr, and furnaces producing as much as 250 tons of iron per heat are in use.

Bessemer-Converter Processes. About the same time that the open-hearth furnace was invented, Henry Bessemer developed this refining process which requires no fuel. The heat is supplied by the oxidation of the impurities in the pig iron. Fig. 7.2 shows that the oxidation of calcium produces the most heat, silicon less, and so on. Silicon and manganese occur in pig iron in sufficient quantities to increase the temperature of the molten iron when they are oxidized by even a blast of cold air. The Bessemer process takes advantage of this by blowing cold air in at the bottom of a pear-shaped vessel (see Fig. 7.11) which has just been filled with molten pig iron from a blast furnace. As the air bubbles through the iron, Si and Mn are oxidized to form a slag and the temperature gradually rises. Carbon is then

oxidized and burns with a long flame from the mouth of the converter. After the carbon "blow," recarburizers and ferroalloys are added, and the charge is dumped and cast into ingots.

In the *acid Bessemer* process, most of the silicon and manganese are eliminated by the slag, but all the phosphorus and sulfur remain. Phosphorus and sulfur in the pig must, therefore, be less than the maximum allowable in the steel. *Basic Bessemer* is not used in the United States because its principal raw material, low-silicon high-phosphorus pig iron, is uncommon in this country.

Since silicon supplies most of the heat in the Bessemer process, the quantity of silicon in the pig iron is held nearly constant so that the steels produced will be as uniform as possible. A Bessemer blow takes only 10 or 12 min and produces 25 tons of steel. One Bessemer converter can keep about two blast furnaces busy.

Because this refining process is rapid and simple, pig iron is sometimes refined in a Bessemer before being charged into the basic open hearth. The silicon is eliminated in the acid Bessemer where it does no harm, and the carbon is reduced in the Bessemer, where the process is rapid. Consequently, the length of heating in the hearth is shortened, and since the sulfur and phosphorus are reduced in the hearth, a very clean steel is produced. This method is known as *duplexing*.

Electric-Furnace Processes. The development of electric furnaces has been a boon to the steel industry because higher and more accurately controlled temperatures are obtainable, and because the charge may be exposed to an atmosphere that will not contaminate the metal. The high cost of electric power is the limiting factor and accounts for electric furnaces being used only for high-quality steel production, usually tool steels and alloy steels. Two types of furnaces are in general use for melting and smelting: the arc furnace and the induction furnace.

Some arc furnaces have been built for single-phase and for d-c operation in which the molten metal is one electrode and a carbon stick is the other. Most furnaces, however, are of the three-phase type shown in Fig. 7.12. In these, the metal is heated by current flowing through it and by radiated heat from the arcs. The molten metal is not an electrode; the current flows through this metal only because the resistance of the iron path is much less than the resistance of the air between the electrodes. Suitable regulators keep the electrodes at the right distance above the molten metal.

In the induction furnace the metal is also heated by a current

within itself, but the entire circuit of the current is within the metallic charge, being induced by means of a strong magnetic field. Fig. 7.13 shows a simple induction furnace in which the magnetic field is set up
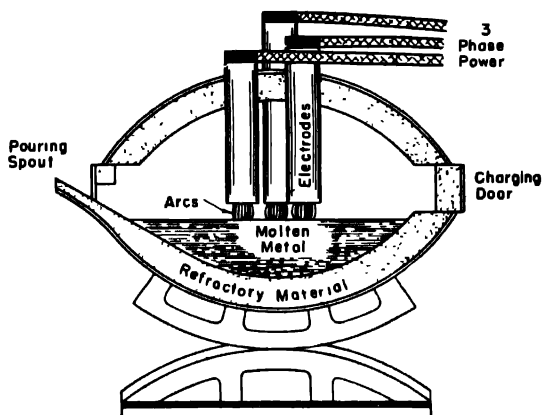
FIG. 7.12. Elementary cross section of three-phase electric arc furnace. Electricity flows through the metal because the total resistance of this path is smallest. Mechanisms on the electrodes automatically regulate the length of the arcs.

by a coil of wire around the crucible containing the metal. The higher the frequency of the alternating current in this coil (voltage remaining constant), the better the heating effect. Frequencies of about 1000 cycles are in common use because they are readily obtainable, whereas higher frequencies require expensive generators. The heat-
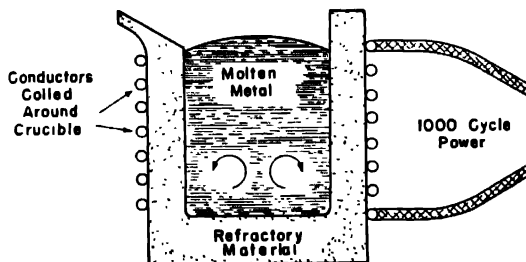
FIG. 7.13. Elementary cross section of induction furnace. Current in the coil induces currents in the metal (as shown by arrows), causing heat. Conductors are water cooled.

ing effect of the induction furnace is analogous to the heat generated in the secondary of a transformer. The coil on the furnace is usually a copper tube and water is circulated through it to keep it cool.

The electric furnaces can produce steel of almost any desired purity and composition because various fluxes may be used and the operator can take samples of the melt from time to time, analyze them, and add whatever is needed to bring the steel to the desired composition.

Crucible Process. All steels were made in crucibles before the invention of the open hearth and the Bessemer converter. The crucible is a ceramic cup, or vessel, in which are placed materials in the right amounts to give steel of the proper final composition. The crucible is then heated until the charge is molten and ready to pour into ingots. Except for removal of gases and nonmetallic inclusions, little refining action occurs in the crucible, and the process is therefore not used extensively.

7.18 THE CASTING OF STEEL

The molten steel coming from the refining furnaces may either be cast into the desired shape in which it will be used, or it may be cast into an *ingot* and then rolled, forged, hammered, pressed, or machined into the desired shape. Most steel mills are arranged in such a way that the refining furnaces take molten pig from the blast furnaces, refine it, and cast it into ingots which are kept hot until ready for the blooming or rolling mill. In this way the iron is not cold from the time it enters the blast furnace as iron ore until it is a finished steel shape.

After steel has been refined in an open hearth or Bessemer, it is apt to contain oxygen in the undesirable forms of iron oxide and dissolved gas. The carburizer that is added to bring the carbon content of the steel up to the desired amount tends to deoxidize the iron, forming CO_2, which bubbles up and causes "boiling" in the ingot before the steel solidifies. Some of the gas becomes trapped during solidification and forms *blowholes* or voids in the ingot. Steel cast in this way has a characteristic solid rim of metal next to the mold, and is called *rimmed steel*. It has a smooth surface, and products rolled from these ingots (strip, sheet, plate) have an excellent surface finish. Blowholes deep in an ingot may cause no harm if the ingot is to be rolled, because the rolling takes place at welding heat, and the holes are effectively welded together. Blowholes near the surface, however, may break out in cracks which no amount of mechanical work will eliminate.

To minimize the occurrence of blowholes the steel may be *killed* by adding other deoxidizing materials to the ladle just before cast-

ing.   Aluminum, vanadium, silicon, and manganese effectively deoxidize iron and carbon (see Fig. 7.2) and are most commonly used.

Steel ingots are cast in a cast-iron mold.   The molten metal is introduced into the mold either from the top or from the bottom. The liquid next to the mold walls solidifies first, and the solidification progresses inward.   There are definite directional tendencies in the grain growth, as explained in Chapters 1 and 2; and, in addition to coring within the individual grains, the grains differ somewhat in both composition and structure from the surface to the center of the ingot.   The contraction of the metal during cooling causes a cavity, or pipe, at the top of the ingot, which extends downward at the center.   Usually the ingots are provided with a "hot top," or small reservoir of metal, which feeds the ingot as it solidifies and thus prevents a large pipe from forming in the ingot.

Segregation also takes place as the ingots freeze.   Dissolved elements, such as carbon, phosphorus, and sulfur, are less soluble in the solid iron than in the molten iron, and they tend to migrate from the solidifying steel into the neighboring molten steel.   The molten steel therefore becomes higher and higher in impurities and often the metal near the pipe is very "dirty" because it has solidified last.   When this may cause difficulty in use, the steel is often purchased under an "ARR" (additional restrictive requirement) which calls for cropping the pipe section more than usual before rolling.   Control of segregation is difficult, but it is generally true that the more impure a steel is, the greater the tendency it has to segregate.   The carbon-tool steels and spring steels must be cast in small ingots to lessen the chance for carbon migration before the whole mass solidifies.   Some alloy steels are also handled in this way.

7.19   STEEL CASTINGS

Approximately 1 million tons of steel castings are produced for commercial use in the United States each year.   These castings are generally divided into five classifications:

(1) Low-carbon steels (carbon content below 0.20 per cent).

(2) Medium-carbon steels (carbon content between 0.20–0.50 per cent).

(3) High-carbon steels (carbon content above 0.50 per cent).

(4) Low-alloy steels (alloy content less than 8 per cent).

(5) High-alloy steels (alloy content above 8 per cent).

All the carbon steels contain less than 1.7 per cent C, along with other elements, usually in the range of 0.50–1.00 per cent Mn, 0.20–0.70 per cent Si, 0.05 per cent max P, and 0.06 per cent max S, plus small amounts of other elements from the scrap used. Most of the castings produced are of the medium-carbon grade. Lower- and higher-carbon-content grades are considered only for special product applications.

Steel castings are considered of alloy grade if the residual or added alloying elements exceed 1 per cent Mn, 0.70 per cent Si, 0.50 per cent Ni, 0.50 per cent Cu, 0.25 per cent Cr, 0.10 per cent Mo, and 0.05 per cent V, W, Al, or Ti. Phosphorus and sulfur are limited as for the carbon-steel casting grades. The low-alloy class is the second largest production of all the steel-casting groups. High-alloy castings are utilized for special heat and corrosion resistance, and they find limited specialized applications.

At least 75 different compositions are used commercially in these classifications. The railroad and transportation industries use 35 per cent of the castings produced. Other large applications are machinery parts 25 per cent, rolling-mill components 15 per cent, material-handling equipment 8 per cent, valves and pressure fittings 7 per cent, and road and building construction 5 per cent.

The mechanical properties of the cast steels are best summarized in terms of properties of the wrought steels. At equal hardness the cast grades have equal strength to wrought or welded grades. Ductility is often lower than for wrought material tested in the direction of working, but is higher than for transverse directions. The same differences, although usually more marked, occur with impact strength. The reversed bend endurance ratio to tensile strength varies from 0.42 to 0.50 for the cast steels, depending on the composition and heat treatment. The range of mechanical properties available is indicated by Table 7.4, taken from two ASTM minimum specifications.

Other properties, too, are similar to the wrought steels of the same composition, structure, and hardness. For wear resistance, cast steels of 0.50 per cent C have given excellent service as have low-alloy cast steels with Cr, Cr-Mo, Ni-Cr, Cr-V, and medium Mn, all with 0.40 per cent C or more. For corrosion resistance, copper additions improve resistance to atmospheric attack, and high-alloy cast steels of the Cr or Cr-Ni type are used for the more corrosive conditions. Alloys with 4–6.5 per cent Cr, especially with additions of 0.75–1.25 per cent W or 0.40–0.70 per cent Mo and

Table 7.4   ASTM Requirements for Steel Castings, Mechanical Properties

Grade	Tensile Strength, Minimum, psi	Yield Point, Minimum, psi	Elongation in 2 In., Minimum, per cent	Reduction of Area, Minimum, per cent
ASTM, A 27–1946 T *				
60–30	60,000	30,000	24	35
65–35	65,000	35,000	24	35
70–36	70,000	36,000	22	30
ASTM, A 148–1946 T †				
80–40	80,000	40,000	18	30
80–50	80,000	50,000	22	35
90–60	90,000	60,000	20	40
105–85	105,000	85,000	17	35
120–100	120,000	100,000	14	30
150–125	150,000	125,000	9	22
175–145	175,000	145,000	6	12

* Carbon steel for miscellaneous industrial uses.
† Alloy steel for structural purposes.   See other ASTM specifications for other grades and uses.

0.75–1 per cent Ti, have good strength and considerable resistance to scaling to 1000 F, but they are not comparable to the high-alloy nickel-chrome types.   Weldability, hardenability, and machinability all compare with wrought steels of similar composition and strength, although the cast surface skin is itself difficult to machine unless a deep, or hogging, first cut is used.

7.20   HEAT TREATMENT OF STEEL CASTINGS

Heat treatments of steel castings are quite similar to those to be discussed later for wrought steels of similar shape and composition.   The operations performed are stress relieving, annealing, normalizing, quenching, tempering, and case hardening.

Stress Relieving.   For relief of internal stress temperatures from 900 to 1000 F are usually used, and the castings are slowly cooled after uniform heating to this value.   Stresses are usually reduced by 90 per cent or more and there is little effect on strength or ductility.

Annealing.   In this operation castings are heated at a rate of 150–200 F/hr to about 200 F above the transformation temperature. After soaking at this temperature, the castings are slowly furnace cooled to 1000 F, after which the rate of cooling is accelerated.

The annealing process has a twofold purpose: (a) to break up large, brittle, dendritic structure formed during solidification and slow cooling, and (b) to promote diffusion of segregated phases. Good ductility and lower tensile, yield, and impact strength result. Usually only carbon steels are given this treatment.

Normalizing. Castings heated to above the transformation temperature, as in annealing, and then cooled in air are said to be normalized. This operation produces somewhat higher strength properties than in annealing. Light sections have higher values than the heavier sections which cool more slowly because of their mass. On higher-alloy cast steels this operation is known as homogenizing. It is employed for these materials to promote diffusion of carbon and to break up the cast structure prior to quenching operations for hardening.

Quenching and Tempering. In quenching cast steel it is usually heated to 100 F above the transformation temperature, held at this temperature for ½ to 1 hr to assure complete austenitization, and then quenched directly in water or oil, whichever is needed to develop martensitic structure.

Tempering consists of reheating to temperatures of 400–1275 F, holding at temperature for a 1 hr/in. thickness or 2 hr min (more for low temperatures), followed usually by furnace cooling the castings to some intermediate temperature and air cooling to room temperature. The tempering temperatures chosen depend on the hardness and strength required. Lower temperatures develop the maximum strength; high temperatures the maximum ductility. Stresses caused by nonuniform cooling in the quench are relieved by this operation.

When the size and/or the design are such that direct quenching in a room-temperature bath might cause severe stresses and cracking, the castings may be given an interrupted, or timed, quench. This quench involves removing the castings from the bath when heavier sections have cooled to 500 F. The castings are then allowed to equalize temperature in air (with thinner sections which may be as cool as 250 to 300 F) and are then further cooled to assure completeness of the martensite transformation before tempering. Quenching into a salt bath at 500 F may also be used in this way.

Case-hardening operations may be employed for cast steels in the same manner as mentioned in discussion of wrought steels.

7.21 WROUGHT STEEL

The purpose of working steel mechanically is to change its dimensions, properties, or surface condition. The ingots are usually kept hot in *soaking pits* until it is convenient to hot work them. The top end of the ingot, containing most of the pipe and segregated impurities, is cut off and scrapped. The sound part of the ingot is rolled down to a *bloom*. The bloom, which has a cross-sectional area greater than 36 sq in., may then be rolled down to a *billet*, which has a cross-sectional area between 1½ and 36 sq in., or to a *slab*, which is at least 1½-in. thick, has a width more than twice its thickness, and usually has an area not less than 16 sq in.* These various forms may then be reduced to any of the many finished shapes shown in Fig. 7.14. Most of the shaping is done by hot working in the forging range (see Fig. 7.15).

Fig. 7.16 demonstrates grain growth and refinement in a steel that is solidified from the liquid state, heated again to a forging temperature, and then worked for a certain interval. The figure indicates that the best grain refinement obtained by mechanical treatment takes place if the hot working is continued until the steel has cooled to its critical range.

The hot- and cold-working operations used in industry are discussed in Chapters 18 and 19.

7.22 WROUGHT-STEEL DESIGNATIONS

There are over one thousand varieties of wrought steels available commercially. Perhaps the easiest way to consider them is in relation to the following categories: (1) plain carbon steels; (2) low-alloy steels; and (3) high-alloy steels. Plain carbon steels contain carbon as the most important alloying element. Low or mild carbon designates grades generally with 0.30 per cent or less carbon. Medium-carbon grades contain 0.30 to 0.70 per cent carbon, and high-carbon grades contain from 0.70 to 1.7 per cent carbon. These steels also contain small amounts, usually less than 0.5 per cent, of impurities like sulfur and phosphorus, and of deoxidizing agents, such as magnesiu n, silicon, and aluminum. Smaller percentages of oxygen, nitrogen, copper, nickel, chromium, molybdenum, lead, and arsenic may be present because of the raw materials utilized.

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* American Iron and Steel Institute, *Steel Products Manual,* Section 2, May 1942. These distinctions are in general use but are not universal.
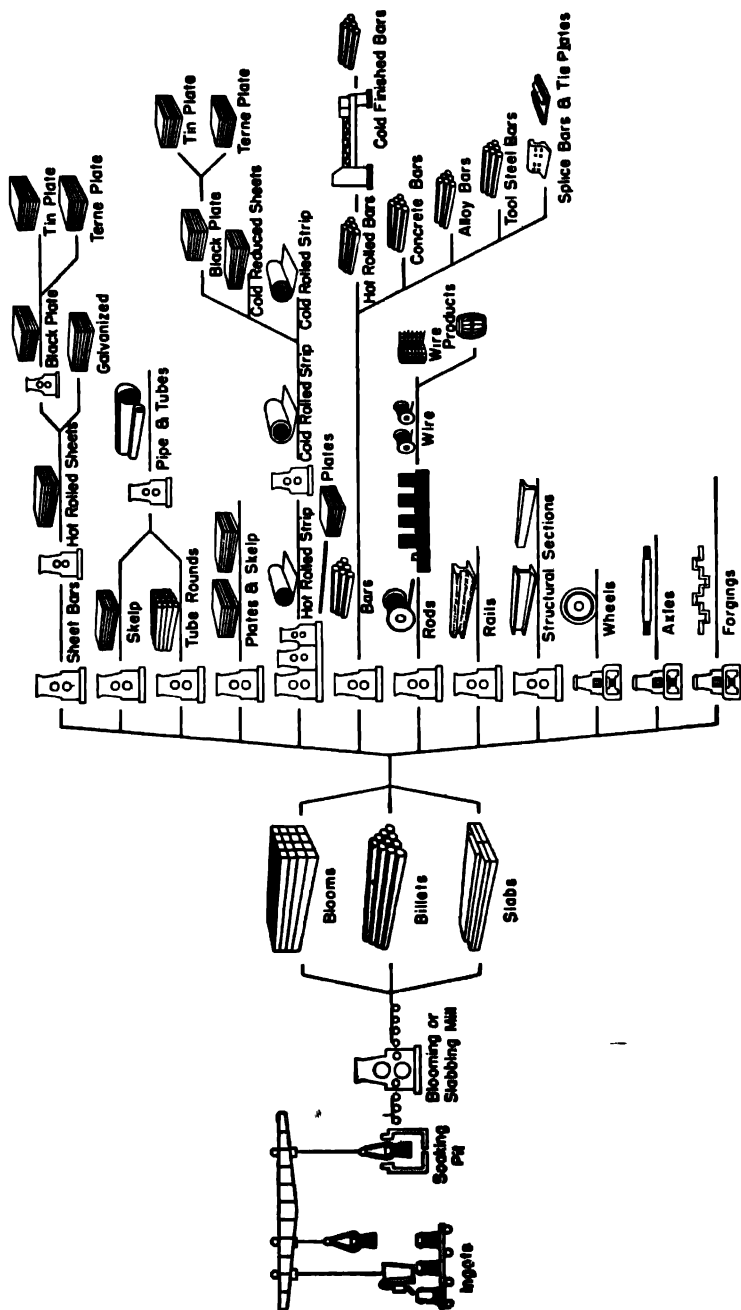
FIG. 7.14. Typical foundry and mill products and methods used to shape them from ingots. (Adapted from Victory Bulletin, Vol. 3, No. 52.)
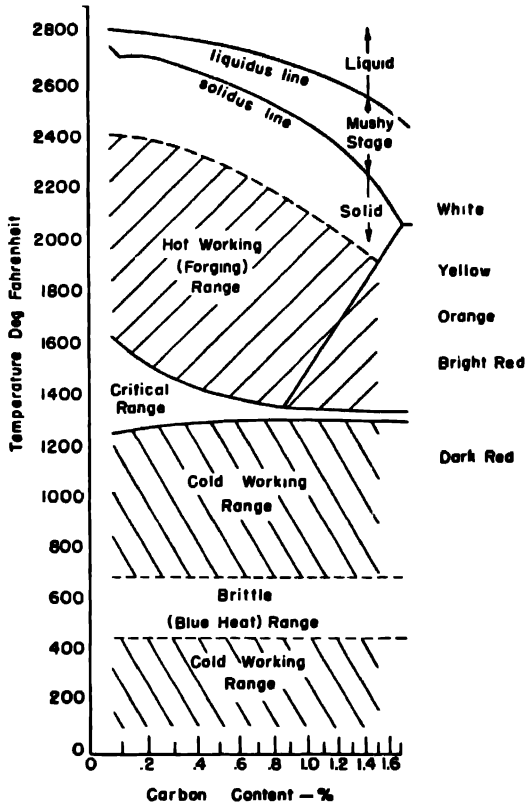
FIG. 7.15. Working temperature ranges for steel.

The alloy grades are thought of as low-alloy steels if one or more of the alloying elements present are within the percentages listed in Table 7.5. Higher-alloy steels contain, of course, more alloying element or elements than one or more of the limits in Table 7.5.

Table 7.5 Alloying Limits for Low-Alloy Steels

Alloying Element	Per Cent
Chromium	0.15 to 3.50
Copper	0.15 to 1.50
Manganese	0.70 to 2.0
Molybdenum	0.10 to 0.50
Nickel	0.4 to 5.5
Phosphorus	0.065 to 0.15
Silicon	0.50 to 5.0
Vanadium	0.15 to 0.25

Many of the grades in these three categories are produced according to chemical and physical specifications prepared by such groups as the American Iron and Steel Institute (AISI), the Amer-
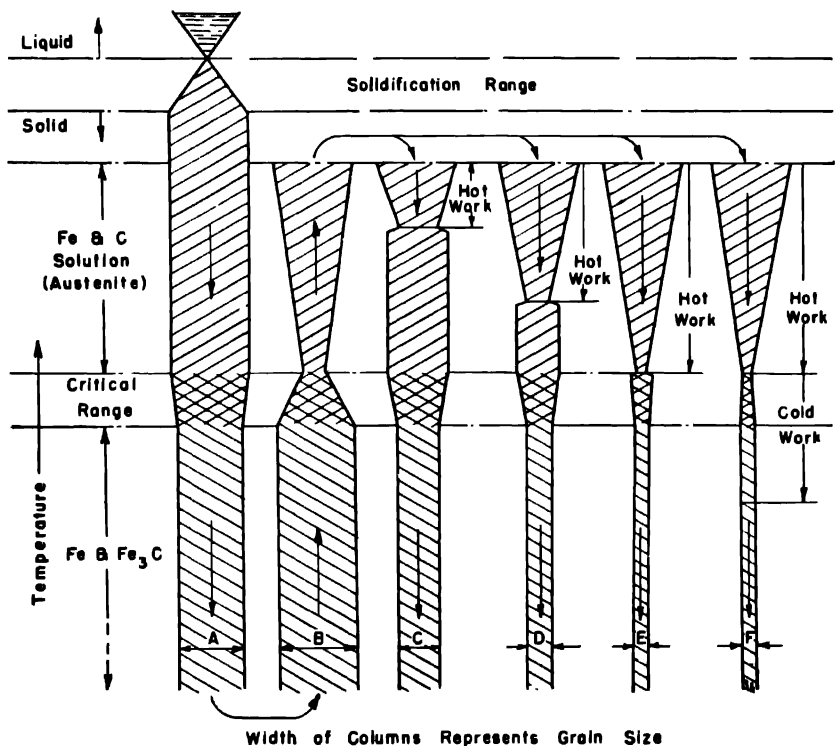
FIG. 7.16. Effect of mechanical working on grain size of steel: (a) liquid steel cooled to room temperature (grains form upon solidification, re-form to smaller grains in critical range); (b) steel heated to high temperature (reduction of grain size in critical range and then growth above this range); (c) small amount of hot working (grains are refined, but grow again to size characteristic of temperature at which hot work is stopped); (d) larger amount of hot working (grains have less chance to grow); (e) hot working to critical temperature (grains cannot grow; maximum refinement is attained); (f) working below critical (the cold work causes no further refinement; only distortion of grains results).

ican Society of Testing Materials (ASTM), and the Society of Automotive Engineers, (SAE). Often the producers have their own identification systems or trade names for their products. And many of the large industrial consumers have their own specification systems for purchasing steels. As a result, there are many identifica-

tion systems in use in engineering practice. The AISI system is probably the most widely adopted. It covers the plain carbon and low-alloy steel categories and will be used for convenience in identification of illustrative data to be included with succeeding paragraphs.

The AISI numbering system for steels is essentially the same as the old SAE numbering system, and the numerals used are standardized for both. The first digit of the usual four-numeral designation indicates the type to which the steel belongs. The second digit for the simple low-alloy steels indicates the approximate percentage of the predominant alloying element. The third and fourth digits (and the fifth for one group) usually indicate the mean per cent carbon content. Thus the designation 2330 indicates a nickel steel, approximately 3 per cent (3.25–3.75 per cent) nickel, and an average of 0.30 per cent (0.28–0.33 per cent) carbon content. The basic numbers for the various grades of carbon and alloy steels are given in Table 7.6.

A letter prefix is added to these numerals to indicate the manufacturing process employed in producing the steel. The prefixes used and the processes indicated are:

B: denotes acid Bessemer carbon steel.
C: denotes basic open-hearth carbon steel.
CB: denotes steel that may be either Bessemer or open hearth at the mill's option.
E: denotes electric-furnace alloy steel.
No prefix is used for open-hearth alloy steels.

A number of triple-alloy grades were designed in 1943 to alleviate shortages of nickel, chromium, and molybdenum. They were known as the National Emergency, or N.E., steels. Some of them have continued in the postwar period, and it is to be expected that others or modifications will continue to be important in the years ahead.

Subsequently, steel specifications have been developed that designate hardenability limits and allow composition variations (rather than grain-size variations) to achieve the specified hardenability. These steels are known as "H" steels, the H serving as a suffix to AISI numbers. Only a few of these specifications are available at present, but this practice may also be expected to expand for selected low-alloy steels.

Table 7.6   Combined AISI and SAE Standard Designations for Carbon and Alloy Steels

Carbon Steels

10xx   Nonresulfurized basic open-hearth and acid Bessemer carbon steel
11xx   Resulfurized basic open-hearth and acid Bessemer carbon steel

Low-Alloy Steels

13xx   Manganese (1.60–1.90%) steels
23xx   Nickel (3.25–3.75%) steels
25xx   Nickel (4.75–5.25%) steels
31xx   Nickel (1.10–1.40%)—chromium (0.55–0.75 or 0.70–0.90%) steels
33xx   Nickel (3.25–3.75%)—chromium (1.40–1.75%) steels
40xx   Molybdenum (0.20–0.30%) steels
41xx   Chromium (0.80–1.10%)—molybdenum (0.15 or 0.18–0.25%) steels
43xx   Nickel (1.65–2.0%)—chromium (0.40–0.60 or 0.70–0.90%) steels—
      molybdenum (0.20–0.30%) steels
46xx   Nickel (1.65–2.0%)—molybdenum (0.15 or 0.20–0.27 or 0.30%)
      steels
48xx   Nickel (3.25–3.75%)—molybdenum (0.20–0.30%) steels
50xx   Chromium (0.20–0.35 or 0.55–0.75%) steels
51xx   Chromium (mean per cent 0.80, 0.90 or 1.05) steels
5xxxx Chromium steel (mean per cent 0.50, 1.00, or 1.45) with carbon
      0.95–1.10%
61xx   Chromium (mean per cent 0.80 or 0.95)—vanadium (0.10 or 0.15%
      min) steel
86xx   Nickel (0.40–0.70%)—chromium (0.40–0.60%)—molybdenum
      (0.15–0.25%) steels
87xx   Nickel (0.40–0.70%)—chromium (0.40–0.60%)—molybdenum
      (0.20–0.30%) steels
92xx   Manganese (0.85% mean)—silicon (1.8–2.2%) steels
93xx   Nickel (3.0–3.50%)—chromium (1.0–1.4%)—molybdenum (0.08–
      0.15%) steels
94xx   Manganese (1.0% mean)—nickel (0.30–0.60%)—chromium (0.3–
      0.5%)—molybdenum (0.08–0.15%) steels (formerly N.E. type)
97xx   Nickel (0.40–0.70%)—chromium (0.1–0.25%)—molybdenum (0.15–
      0.25%) steels (formerly N.E. type)
98xx   Nickel (0.85–1.15%)—chromium (0.70–0.90%)—molybdenum
      (0.20–0.30%) steels (formerly N.E. type)
99xx   Nickel (1.00–1.30%)—chromium (0.40–0.60%)—molybdenum
      (0.20–0.30%) steels (formerly N.E. type)

7.23   THE CONSTITUENTS OF STEELS

The constitution diagram for iron-carbon alloys, Fig. 7.5, indicates the compositions and the equilibrium conditions for occurrence of the three principal phases of steels. These phases are ferrite, cementite, and austenite. The many elements besides iron and carbon that are present in steels, either as impurities or alloying

elements, do not, in general, alter the characteristic features of the iron-carbon constitution diagram. The positions of the boundary lines are shifted, however.

By combining experimental and theoretical results it has been determined that nitrogen, manganese, nickel, zinc, and copper, in order of decreasing effect, shift line $GS(A_3)$ to the left; chromium and cobalt have little effect; and tungsten, molybdenum, silicon, vanadium, tin, aluminum, beryllium, phosphorus, and titanium, in order of increasing effect by weight-per cent, shift A_3 to the right. The shift is approximately proportional to the percentage of each element, and is algebraically additive for several elements. Similarly, the line $SE(A_{cm})$ is altered by presence of alloying elements, although the effects are somewhat more complicated. Small amounts of manganese, silicon, chromium, copper, molybdenum, and titanium, in order of increasing effect, and of tungsten, vanadium, and probably nickel move the A_{cm} line uniformly to the left. This continues to high percentages for silicon, manganese, copper, and probably nickel, but the other elements tend to introduce new carbide phases. Sufficient alloying element of the latter type causes equilibrium of lower carbon austenite with the new carbide, restricting the region at low temperatures to lower carbon content. The effects of several alloying elements superpose on A_{cm}, but will not add linearly. Effect on the line $PS(A_1)$ has been little studied, but it is known that the line resolves into a three-phase region whose upper and lower boundaries are not necessarily horizontal. Thus, alloying elements in steel displace the phase boundaries shown on Fig. 7.5 but its features may be employed in studying the phase transformations involved.

Steel as received from the mill usually consists of ferrite and cementite. Solid solutions of which α-iron is the solvent may be called *ferrite* (see Fig. 7.17).* It forms from the gamma (austenitic) phase in slow-cooled alloys, within the field bounded by GSP (Fig. 7.5). Unless it has been hardened by cold working, ferrite is soft (50 to 100 Brinell) and is usually ductile. It may contain in solid solution manganese, silicon, chromium, nickel, and numerous other elements, but very little carbon.

Cementite is the intermetallic compound of carbon and iron, Fe_3C. It is very hard (approximately 1400 Brinell) and brittle, and ap-

* All photomicrographs in this chapter are by members of the Turbine Division, Laboratory of the General Electric Co., Schenectady, New York.

FIG. 7.17. Ferrite in commercially pure (Armco) iron ×100 (*by E. D. Reilly*).

FIG. 7 18 Spheroidal, lamellar, and boundary cementite in annealed high-carbon steel ×1000 (*by E. D. Reilly*).

FIG. 7.19. Diagram showing the formation of the various structures of plain carbon steels. (*Adapted from The Working, Heat Treating, and Welding of Steel, by H. L. Campbell, John Wiley & Sons, New York, 1941, p. 61.*)

pears in the annealed steel as parallel plates (lamellar layers), as rounded particles (spheroids), or as envelopes around the pearlite grains (see Fig. 7.18). This phase is formed in slowly cooled solid alloys within the field *ESK*. In alloy steels, it may contain, besides iron and carbon, one or more of the added "carbide-forming" elements.

Annealing, normalizing, and hardening of steel require formation
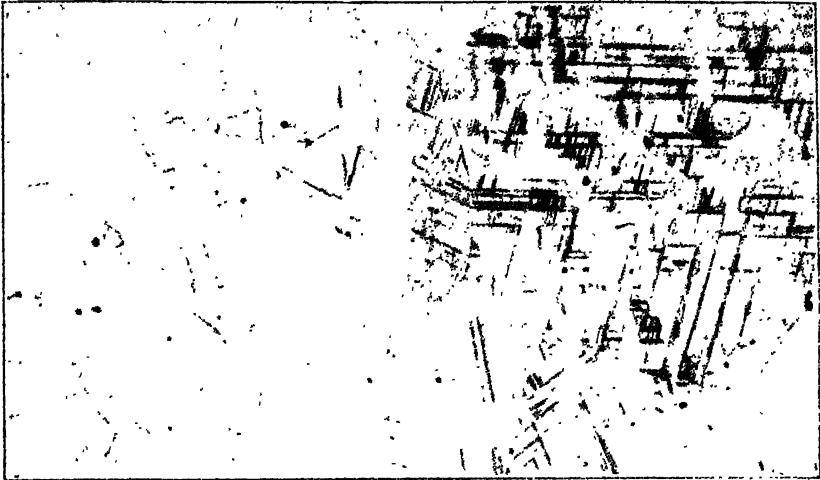
Fig. 7.20. *Left*, austenite in 18 Cr–8 Ni stainless steel ×250 (*by E. D. Reilly*). *Right*, austenite in "nonmagnetic" (16 per cent Mn) cast steel ×100 (*by Joyce Thomas*).

of austenite, the solid solution of which γ-iron is the solvent. This is accomplished by heating into the range above *GSE*, where austenite is a stable phase. The ferrite and carbide react at their interface to form nuclei of austenite, which grow, absorbing the ferrite and cementite. Nucleation and growth require time, and proceed more quickly at higher temperatures. An increase of 50 to 100 F appears to speed the reaction tenfold. Since carbides, particularly of alloys, dissolve more slowly than ferrite, higher temperatures are employed for reasonable austenitization time when alloy carbides are present in moderate quantities.

STRUCTURES RESULTING FROM CONTINUOUS QUENCHING AND TEMPERING. As has been discussed in Chapter 2, nonequilibrium cooling of austenite retards the normal phase transformation indicated by the constitution diagram. The principal structures resulting from various rates of continuous cooling and from subsequent reheating,

or tempering, treatments are indicated in Fig. 7.19. The temperature at which the transformation of austenite occurs is displaced from A_1 during cooling rates used in commercial heat treating. Lines indicating the displaced transformation temperature are designated by subscripts r* for cooling (and c for heating). A_{r1} is included in Fig. 7.5.

Austenite may exist at room temperature only when the normal $\gamma \rightarrow \alpha$ transformation has been fully suppressed. Even when plain high-carbon alloys are quenched very drastically, the resulting structure contains only a small fraction of austenite. Therefore austenite rarely appears in any quantity in plain or low alloy steels. Manganese, nickel, and certain other elements are very effective in suppressing the $\gamma \rightarrow \alpha$ transformation, and even slow-cooled alloys containing certain relatively high percentages of these elements are completely austenitic at room temperature (see Fig. 7.20). Austenite is generally soft and quite ductile, unless cold worked. At elevated temperatures the austenitic steels are stronger and less ductile than the ferritic. Austenite is also more dense than ferrite, its electrical resistance and thermal coefficient of expansion are higher, and it is practically nonmagnetic (paramagnetic). Cold plastic working or chilling in liquid air will often cause "retained" austenite to transform spontaneously to martensite.

Martensite, the principal structure in fully hardened steels, is formed by a shearing mechanism (rather than nucleation and growth through diffusion, as austenite is formed) in carbon steels by fast continuous cooling of austenite to temperatures usually of 400 F to 600 F or lower. It has a tetragonal crystal structure which may be considered as tetragonal ferrite greatly supersaturated with carbon. Some of the carbon may have precipitated during cooling as finely dispersed cementite among the "feathers" or "needles" of the tetragonal structure. The martensitic areas are very hard, 500 to 1000 Brinell, according to carbon content and fineness of structure. They may contain various percentages of "retained" (untransformed) austenite and also "excess" ferrite or cementite, according to the composition of the alloy and its treatment. Several photomicrographs of these combinations are illustrated in Fig. 7.21. "Retained" austenite in martensitic structure is not easily distinguished microscopically, but its presence may be established by hardness, density, or

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* The subscripts r and c come from the French words *refroidir* and *chauffer*, which mean recooling and heating, respectively.
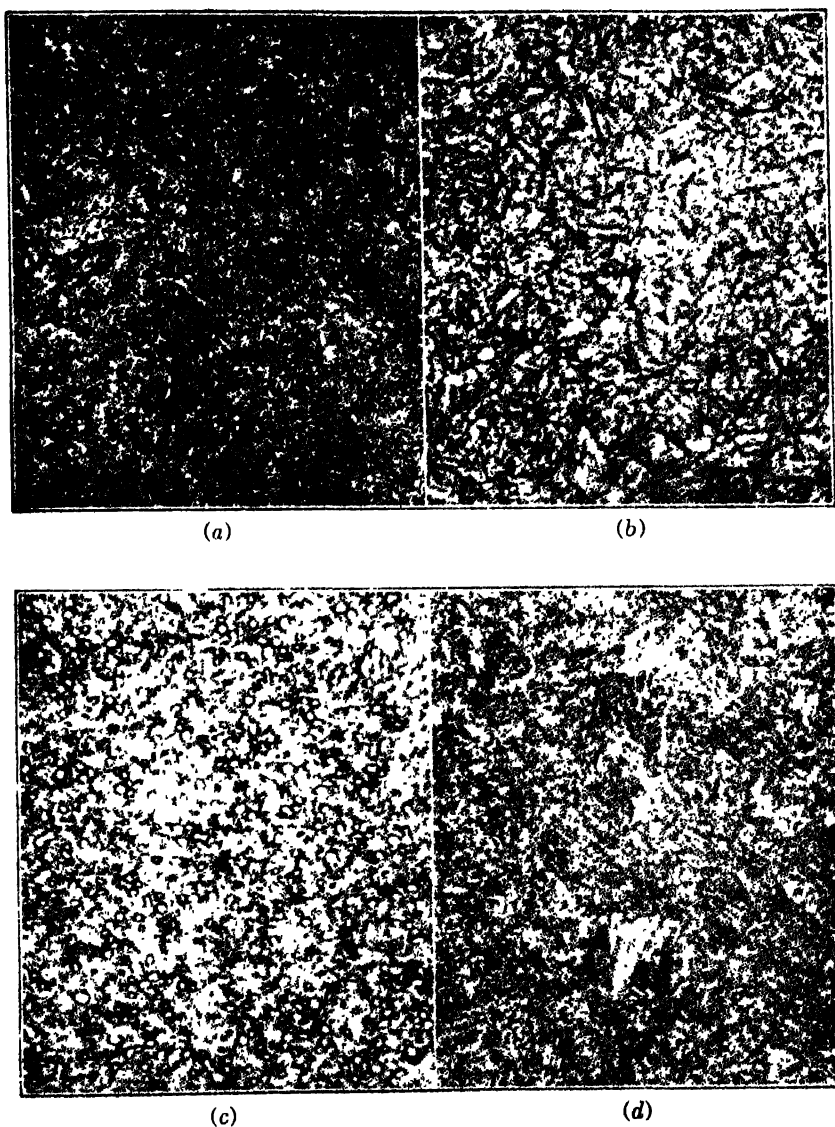
FIG. 7.21. (a) Martensite in 0.50 per cent C steel, 700 Brinell ✕500 (by E. D. Reilly). (b) Martensite with excess cementite in high-speed steel, hardened and tempered ✕500. The white areas are cementite (by E. D. Reilly). (c) Martensite with excess cementite in 1.30 per cent C steel safety razor blade, 800 Brinell ✕1000. The white areas are cementite (by R. N. Gillmor). (d). Martensite with excess ferrite, 500 Brinell ✕500 (by J. J. Vrooman).

(e)

Fig. 7.21 (Cont.). (e) Martensite and retained austenite in high speed steel, hardened but not tempered 800 Brinell ×500 (by E. D. Reilly).
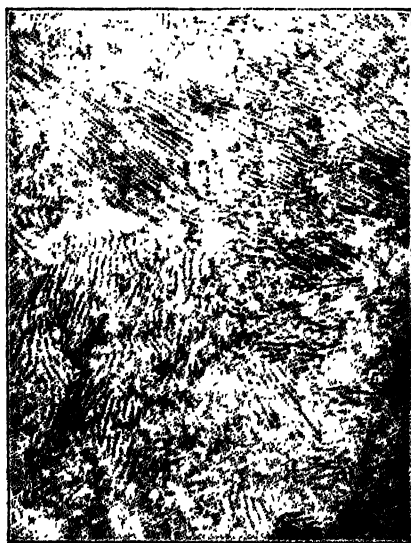
Fig. 7.22. Pearlite in eutectoid (0.83 per cent C) steel ×1000 (by D. B. Blackwood.)

magnetic tests. Martensite is less dense than pearlite or spheroidite, owing to the metastable tetragonal lattice. Therefore, an increase in volume takes place in steel when it is fully hardened.

Pearlite consists of alternate layers of ferrite and cementite in the proportions 87 to 13 by weight. The areas of pearlite are formed spontaneously from slow cooling austenite through the temperature of the line *PSK*, Fig. 7.5. A photomicrograph of pearlite is illustrated in Fig. 7.22. Note that pearlite is the *eutectoid structure* of two phases in iron-carbon alloys.

Steels containing less than 0.83 per cent carbon are called *hypoeutectoid* steels, and those which contain more are called *hypereutectoid*. This terminology applies only to plain and low-alloy steels. With high-alloy steels the eutectoid composition is altered and the structure may not even exist. To distinguish between the ferrite and cementite phases of the pearlite structure, the separate ferrite in hypoeutectoid steels and the corresponding cementite of hypereutectoid steels are known as "free" or "excess" ferrite and cementite respectively. Photomicrographs of pearlitic steels with excess ferrite and cementite are illustrated in Fig. 7.23. An electron micrograph of pearlite with excess cementite is illustrated in Fig. 7.24. The properties of pearlite are, of course, a composite of those of ferrite and cementite.

With faster cooling, pearlitic structure may continue to form down to temperatures of 900 F, the spacing between layers becoming finer at the lower temperatures of formation (see Fig. 7.25). The hardness increases with the fineness of this spacing, ranging from 170 to perhaps 400 Brinell.

Spheroidite is the structure in which cementite takes the form of rounded particles, or spheroids, instead of plates. Just as the spacing varies in pearlite so does the size of the spheroids, as illustrated in Fig. 7.26, the finer-grained material being the harder and stronger. Spheroidite is softer and more ductile than pearlite, but not as freely machinable. It may form directly from slow cooling hypereutectoid austenite which contains undissolved excess cementite, present because the alloy has not been heated above the line *SE*, Fig. 7.5. Also, lamellar pearlite may be spheroidized by heating the steel for relatively long periods of time just below the eutectoid transformation (Fig. 7.27). Spheroidite may also be produced by heating martensite or the temper structures of martensite in the range just below the eutectoid transformation.
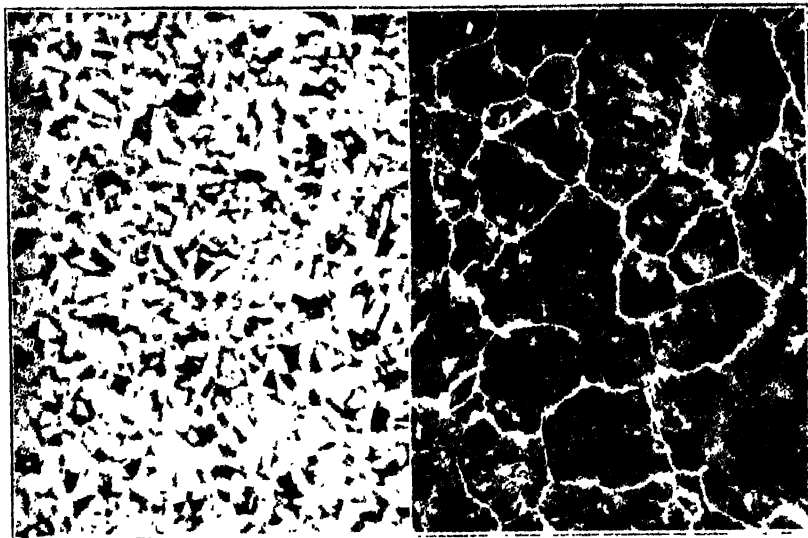
Fig. 7.23. *Left,* pearlite and "free" ferrite (light grains) in hypoeutectoid (0.30 per cent C) steel ×100 (*by W. G. Conant*). *Right,* pearlite and "free" cementite (light areas) in hypereutectoid (1.0 per cent C) steel ×100 (*by D. B. Blackwood*).
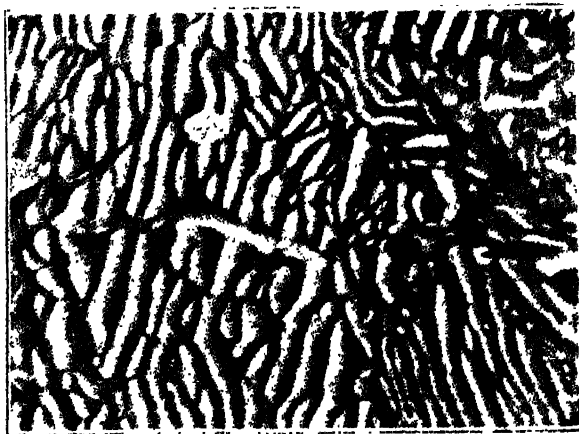
Fig. 7.24. Electron-micrograph of 1.1 per cent C steel showing excess cementite and pearlite. The light regions are cementite. ×10,000 (original ×5000) (*by Research Laboratory, General Electric Co.*).
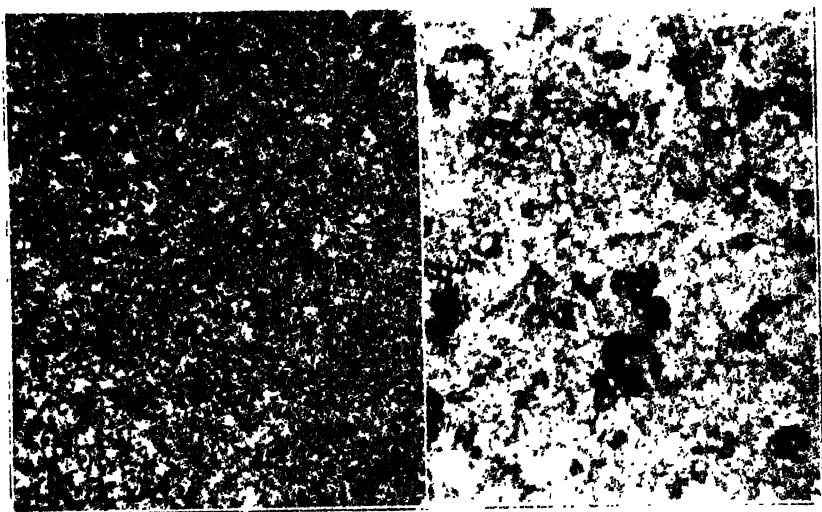
FIG. 7.25. *Left,* fine pearlite (dark) and martensite (light) in incompletely hardened high carbon steel ×100 (*by E. D Reilly*). *Right,* fine pearlite under high magnification. This structure is sometimes called "primary troostite." ×1000 (*by E. D. Reilly*).
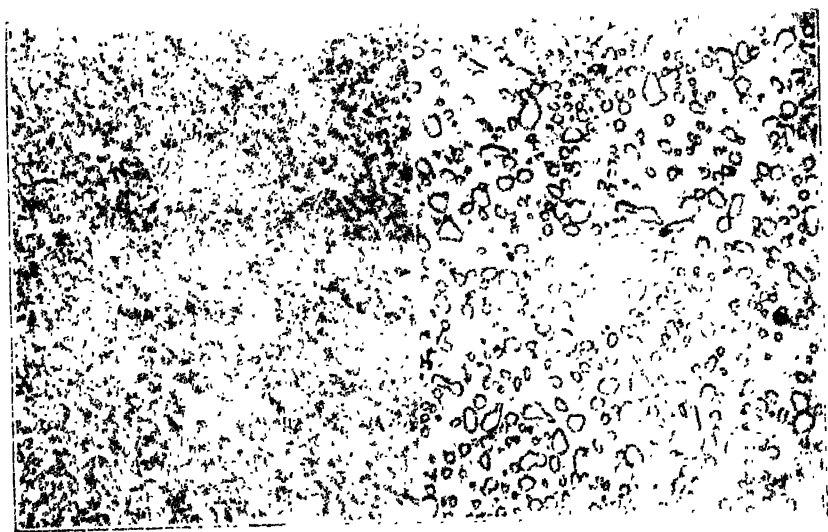
FIG. 7.26. *Left,* spheroidite—fine spheroids—C 0.9. Mn 2.0, Mo 1.0. Brinell 230 ×1000 (*by R. N. Gillmor*). *Right,* spheroidite—large spheroids—C 1.60, Cr 12, Mo 1.0, Va 0.25. 216 Brinell. ×1000 (*by R. N. Gillmor*).

If martensite is reheated (tempered) at temperatures (in plain steels) between about 400 and 750 F, a softer, more ductile structure known as *troostite* is formed. This structure is dark etching (see Fig. 7.28) and apparently consists of submicroscopic particles of cementite in ferrite.

The name "primary troostite" may be applied to the fine pearlite structure obtained on direct cooling and illustrated in Fig. 7.25, but the name, troostite, is more generally applied to this "secondary," or tempered, product. Some prefer to think of the structure as tempered martensite of a measured hardness because of the otherwise arbitrary degree of grain growth and agglomeration that may characterize the same structure.

When troostite (in plain carbon steel) is heated in the temperature range 750 to 1100 F, it changes by indistinguishable degrees into a structure known as *sorbite*, in which the cementite has grown until it has a distinctly granular appearance (see Fig. 7.29). It is softer and more ductile than troostite. Tempering at still higher temperatures causes continued grain growth, until the cementite forms the larger spheroids characterized by spheroidite.

Structures Resulting from Isothermal Quenching. In 1930, E. C. Bain and E. S. Davenport * published a paper on the first important investigations of constant temperature (isothermal) transformation of austenite. The method used consisted of quenching a large number of specimens of a steel from above the transformation temperature into a bath of molten lead, lead alloy, or molten salt maintained at a constant subcritical temperature. Specimens were withdrawn after various time intervals, and quenched in iced brine to prevent further change. The structures were then examined microscopically to determine the start and completion of transformation at the given temperature. Similar tests at other temperatures enabled completion of diagrams like Fig. 7.30. Because of their shape they were called s curves, but the designations T-T-T curves or time-temperature-transformation curves are more often used.

Figure 7.30 illustrates the times at which isothermal decomposition begins and ends in a steel containing a moderate percentage of carbide-forming elements. There are two ranges of rapid isothermal decomposition of austenite. The first occurs at about 1150–1250 F

* *Trans. Am. Inst. Mining Met. Engrs.*, Vol. 90, 1930, pp. 117–154. See also *Atlas of Isothermal Diagrams*, Research Laboratory, United States Steel Corp., Kearny, New Jersey, 1943.

FIG. 7.27. Spheroidite in hypoeutectoid (0.20 per cent C) steel formed from pearlite after 500 hr at 1250 F. ×1500 (*by E. M. Eoff*).
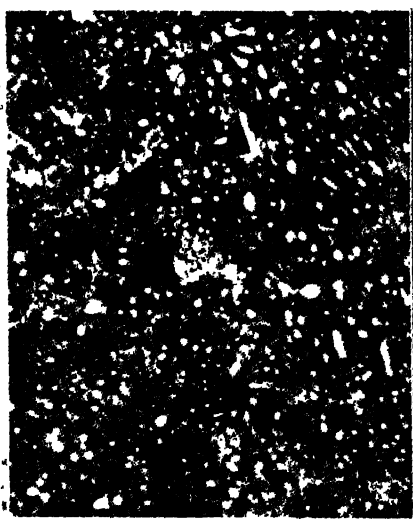
FIG. 7.28. Troostite in plain (1.10 per cent C) steel hardened at 1475 F, quenched in brine, and tempered 1 hr at 550 F. ×1000 (*by E. D Reilly*).
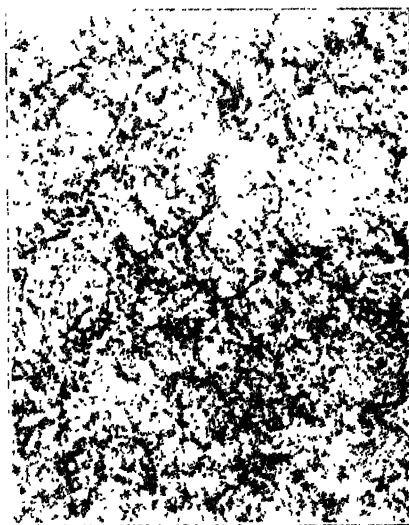
FIG. 7.29. Sorbite in plain (1.10 per cent C) steel hardened at 1475 F, quenched in brine, and tempered 1 hr at 1000 F. ×1000 (*by E. D. Reilly*).

and is associated with decomposition of austenite into lamellar pearl-
ite and proeutectoid ferrite (or cementite for higher-carbon steels).
Coarse pearlite is formed at the upper temperatures of this range;
fine pearlite at the lower temperatures. The second range occurs
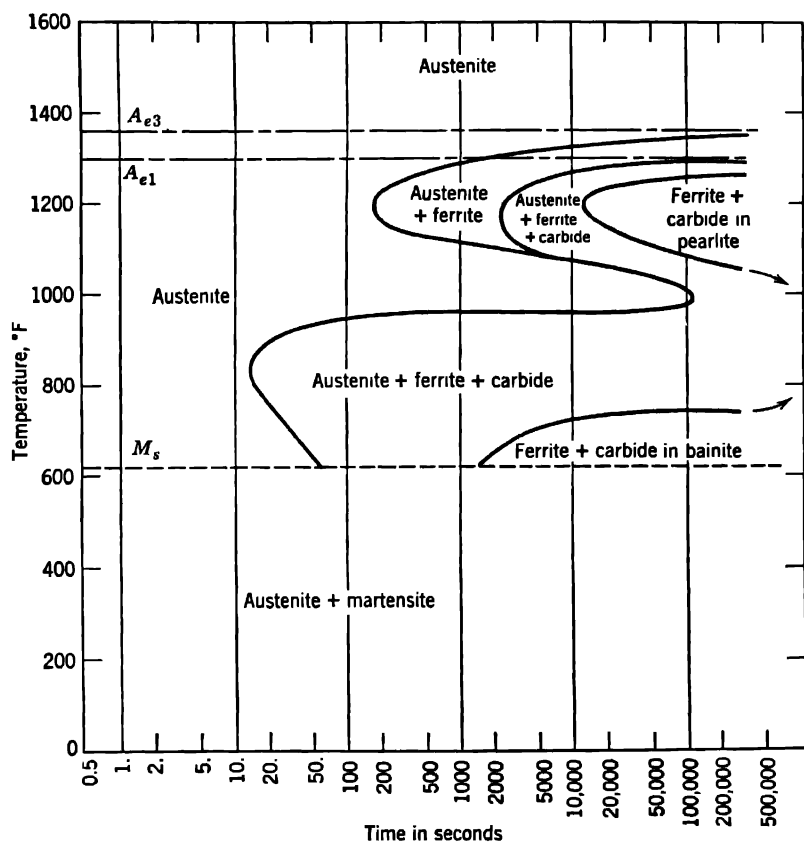
Fig. 7.30. Typical isothermal transformation diagram for steel containing car-
bide-forming elements (AISI 4340).

at 750–950 F and is related to decomposition of austenite into
bainite. The bainite structure was named after E. C. Bain, since
it is formed only by isothermal transformation. It is composed of
ferrite and cementite in a dispersion too fine to be resolved by the
microscope. The structure produced at the lower temperatures of
this range has greater hardness and strength than result at the
higher temperatures of the range.

A third range is indicated on Fig. 7.30 below the M_s line at

620 F. This range is associated with the decomposition of austenite into martensite. The M_s line indicates the start of this transformation. It is influenced greatly by composition and varies from 1000 F to below room temperature for different steels. The
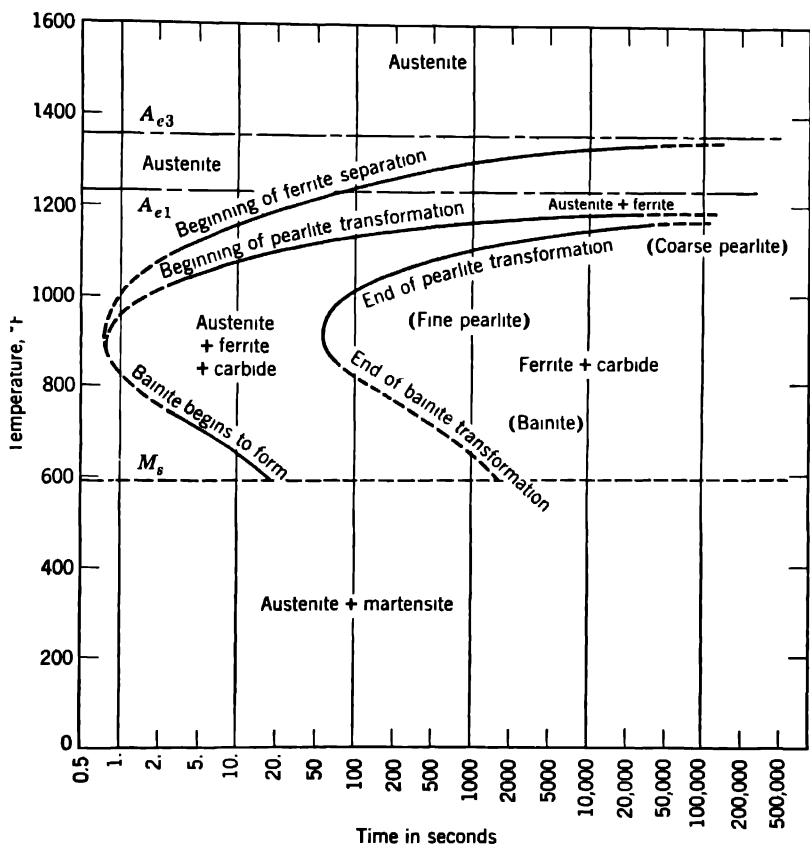
FIG. 7.31. Typical isothermal transformation diagram for steel not containing carbide-forming elements (AISI 2340).

martensite reaction starts, on cooling, at the M_s temperature independent of cooling rate. Once partial transformation has occurred, some stresses are set up in the martensite and the austenite. Further transformation involves establishing additional stresses and hence the energy associated with them. This can occur only by lowering the temperature below the point where transformation began, thus martensite forms *only* under *continuous cooling*.

In steels not containing carbide-forming elements, such as plain carbon steels, the pearlite and bainite ranges have not been segregated. It is possible that these ranges overlap for such steels, or that experimental difficulties have failed to show a region of slow transformation between them. Fig. 7.31 illustrates the T-T-T curve for such a steel. The absence of separate pearlite and bainite "noses" is to be noted.

Tempering of bainite beyond the stage of the nonuniformity of the original precipitate results in structures difficult to distinguish from tempered martensite. The relation of temperature and time for spheroidization and growth in martensite seems to apply also to tempered bainite.

7.24   HEAT TREATMENTS FOR WROUGHT STEELS

Heat treatments are utilized on practically all tool and die steels and other highly alloyed steels. The plain carbon and low-alloyed steels are heat treated to a lesser extent. The treatments used depend on the composition of the material and on its application. Some treatments are performed as part of mill processing; others as part of fabricating the end-use product. All but one of the treatments customarily employed involve phase transformation. The exception is stress-relief annealing which has been covered previously. Each of the phase-transformation treatments of commercial interest is briefly described in following paragraphs.

7.25   ANNEALING

This operation for wrought steels (usually 0.80 per cent C or less) involves slow heating to temperature above the A_3 line, holding at this temperature until austenitization is complete, and then cooling slowly in a furnace at a rate approaching equilibrium conditions. It is used for refining grain of hot-worked products and for improving machinability. It produces lowest hardness, strength, and wear resistance. Temperatures somewhat below A_3 are used for cold-worked products process annealed to improve ductility for further working (see Chapter 1).

7.26   NORMALIZING

In steels containing 1 per cent or more carbon, previous processing treatments involving slow cooling from a high temperature frequently may cause the excess cementite to form a network around the grains. This network is very stable and it makes further heat-

treating operations more difficult because it is unaffected by ordinary annealing temperatures, and it does not go entirely into solution at the regular hardening temperatures. The treatment commonly employed to break up this network and to keep it from reforming is known as *normalizing*. It consists of heating above the A_{cm} temperature line, Fig. 7.5, to dissolve the excess cementite in austenite, and then of cooling at an intermediate rate, e.g., air cooling, so that sufficient time is not allowed for the excess cementite to reform a network or large plates. Instead, the structure is a mixture of fine cementite and pearlite, and is a little harder, stronger, and less ductile than annealed steel of the same composition.

Normalizing is also employed to *homogenize* structures in mild carbon steels, especially heavy forgings. Owing to unequal deformation in hot working, and possible thermal gradients during working, the structure of such parts may not be uniform. The normalizing treatment is performed at a high enough temperature (farther above A_{c3} temperature line than for full annealing) to permit the formation of a uniform austenite solid solution. The normalizing treatment is usually followed by heating to below the transformation temperature to promote softness and improve ductility. Steels given this treatment after normalizing generally have equal or slightly lower strength but greater ductility than before treatment; the two treatments are known collectively as *homogenization*.

7.27   SPHEROIDIZING

If a normalized high-carbon steel is reheated to just below the A_1 line, the fine particles of carbide coalesce into spheres, hence the name spheroidizing. In this condition the steel is soft and readily machinable. More particularly, it is well suited to absorption of carbides during subsequent hardening, which improves the potential hardness. The process is often used as a treatment preliminary to hardening of spring steel.

7.28   QUENCHING

The T-T-T curves are a very useful guide to the quenching rates required to develop desired structure in a particular kind of steel. They also explain why very fast quenching is required for hardening plain carbon steels, whereas alloy steels may be given equal hardness with slower cooling rates. Perhaps the easiest way to utilize the T-T-T curves for these purposes is to superpose on them the cooling curve obtained in quenching.

Since the T-T-T curves are obtained by isothermal quenching, some justification is required for superposing on them the continuous cooling curves obtained by immersion in room temperature water, brine, oil, or air. Studies * have shown that the T-T-T curves are displaced to some extent under continuous cooling conditions. For example, the start of transformation for eutectoid plain carbon steel is lowered and moved to the right—the gate being increased from 1 to 2 sec at 800 F instead of 1000 to 1100 F. Such small changes are important for very small parts like razor blades but would have no influence on heat treatment of most components. With exception, then, of this effect, the continuous cooling curve may be interpreted on the T-T-T curve as a series of short isothermal quenches, each at lower temperature. Intersection of the cooling curve with the T-T-T start curve will indicate start of transformation. Time at this temperature, in proportion to the total time for transformation, may be used to indicate the degree to which the indicated transformation has progressed.

In Fig. 7.32, cooling curve A might represent slow cooling in a furnace, yielding coarse pearlite as shown. Curve B could represent the temperature at the center of a thick bar during water quenching, and curve C could represent the surface temperature for water quenching the same part. Curve C has a cooling rate which is fast enough to avoid any proeutectoid ferrite or cementite, pearlite, or bainite. The transformation on continuous cooling is therefore martensite at the surface. Curve B indicates the center cooled more slowly, and that fine pearlitic structure was formed. This part would therefore show full hardness at the surface grading to fine pearlite at the center for the cooling rate shown.

A cooling curve which enters the knee and recrosses the transformation start curve before crossing the transformation end curve causes a split transformation. A portion of the material transforms where the first crossing occurs, and the remainder where the cooling curve later crosses the bainite or martensite regions. The term *slack quench* is often used to denote this rate of cooling.

The space between the T-T-T curve knee and the vertical axis may be looked upon as a "gate" † through which the cooling curve of the steel must pass for full hardening. The gate in Fig. 7.31 is at about 0.75 sec at 900 F, indicating that a water quench is required. The

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* R. A. Grange and J. M. Kiefer, *Trans. Am. Soc. Metals*, Vol. 29, 1941, pp. 85–116.

† A term coined by H. C. McQuaid.

gate for the steel in Fig. 7.30 is at about 15 sec at 825 F, allowing considerably lower cooling rate for that steel.

The faster cooling rates are hazardous to components because of the stresses introduced. These stresses are partly due to thermal gradients but mainly are the result of the $\gamma \rightarrow \alpha$ transformation. The
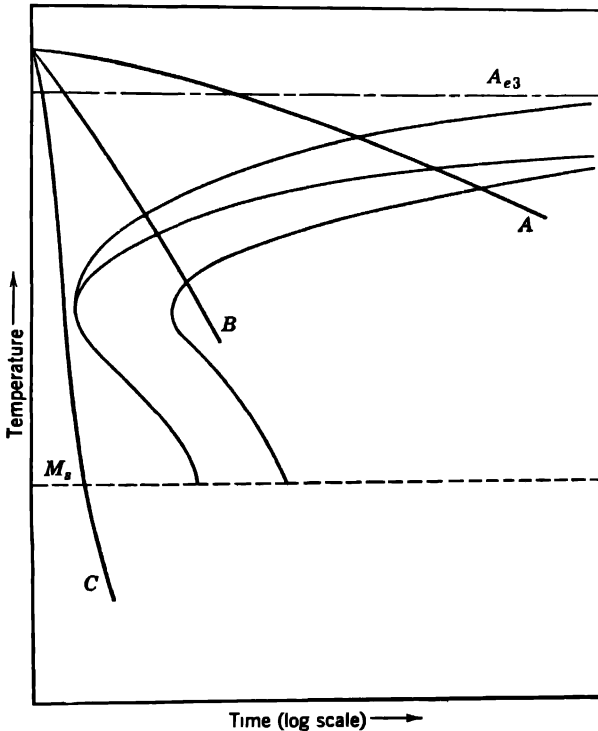
FIG. 7.32. *T-T-T* curve and three cooling curves.

transformation from γ to α is accompanied by a decrease in density because of the "closer packing" of atoms in the face-centered lattice. At 1670 F, the densities of the phases are $\alpha = 7.54$ g/cc, and $\gamma = 7.63$ g/cc. The volume changes may be indicated by an instrument called a *dilatometer*, which measures change in length. The three dilatometer curves in Fig. 7.33 show that the volume changes and transformations occur at lower temperature for faster cooling rates. Since temperature gradients are produced during the quenching operation, the transformations in near adjacent material may take place at different times, producing considerable stress. Design can help mitigate such stresses, as discussed in Chapter 17.

An *interrupted quench* may be used to reduce the stress and distortion produced. The heat treater may quench a part to below the knee in water, and then take advantage of the bay opposite the bainite region to remove the part from the water and quench it from just
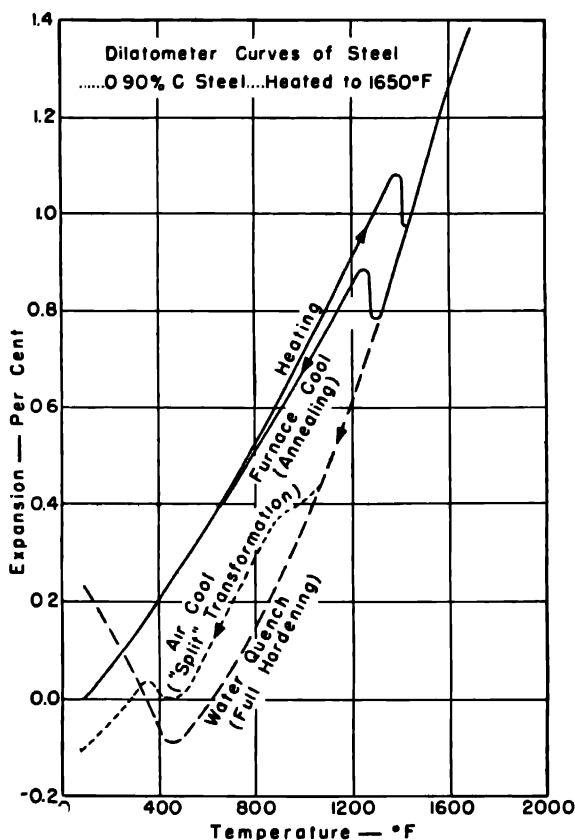
FIG. 7.33. Dilatometer curves of 0.9 per cent C steel, heated to 1650 F and cooled at three different rates.

above the M_s in oil. In some high-carbon and alloy steels the bainite bay is so wide that time is available to straighten or perform other work on the steel while it is still in the ductile austenitic state, without affecting its capacity to harden to martensite.

A process termed *martempering* developed by B. F. Shepherd [*] makes use of this technique. The steel is quenched into a molten bath

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* See *Product Eng.*, July 1945, p. 438, and August 1945, p. 515.

held slightly above the M_s point. The bath is chosen so the quench will exceed the critical rate at the gate. The part thus is quenched
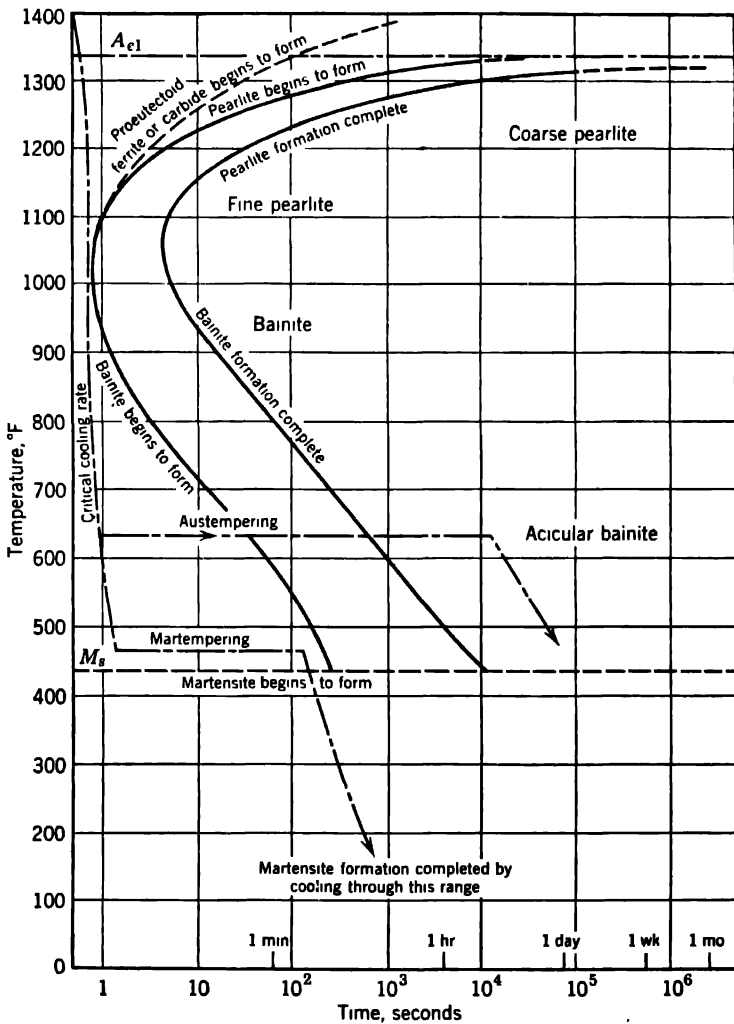
Fig. 7.34 Schematic T-T-T curves for a plain carbon steel. Cycles for martempering and austempering are indicated.

just fast enough to avoid transformation to any higher temperature products. It is maintained in the bath until temperatures are equalized but not long enough for bainite to form. Then it is allowed to transform to martensite by quenching in *air* (see Fig. 7.34). It is

claimed this treatment improves ductility and toughness, for the same hardness, possibly because stress gradients are lower than for continuously quenched steels.

The name given to isothermal quenching of steels in the manner used by Bain and Davenport in developing the *T-T-T* curves is *austempering*. It is used for high-carbon and low-alloy steels of suitable composition and small cross section ($\frac{1}{2}$-in. thick or less). Such parts are quenched in a bath at the temperature which produces the desired structures. After holding in the bath for the time required for the transformation to end, the part is removed and cooled to room temperature in air (see Fig. 7.34). The process cannot be used to develop a very hard martensitic structure, such as is obtained by water quenching and tempering at 200 or 300 F. However, bainite structure corresponding to tempered martensite of any required degree of fineness may be produced. Steels so treated are more ductile and tough than similar steels quenched to room temperature and tempered to produce corresponding structure with equal hardness and tensile strength. Freedom from submicroscopic cracks resulting from the drastic quench to martensite is advanced as the explanation.

Patenting is an old process used for heat treating medium and high-carbon rods that are to be cold drawn into high-strength wire. The rods, or wire (if the stage is intermediate), are heated well above A_3 to cause grain growth. Quenching then takes place in air or in a molten lead bath at 850–950 F. The resulting structure consists of large pearlitic grains composed of fine ferrite and cementite. An elongated "fibrous" structure results in the finished wire, which apparently resists the propagation of minute cracks in bent shapes better than high-carbon wire cold drawn, quenched, and tempered.

7.29 TEMPERING

As has been discussed, tempering is used to control the structural precipitation and growth from martensite to obtain desired combinations of strength and toughness. The fully hardened steel may be reheated in a furnace, in heavy oil, in a salt bath, or in molten lead. It is held long enough for heat to penetrate the center. For most steels the speed of cooling after tempering is of little consequence, provided the upper temperature is below A_1. Cooling is therefore usually accomplished in air.

The typical decomposition products that occur in tempering are transformation of tetragonal to cubic martensite; precipitation,

growth, and spheroidization of iron carbide; and precipitation, growth, and spheroidization of alloy carbides.

Another type of precipitation from ferrite may occur at temperatures below the critical. It has been reported only in steels containing more than 0.6 per cent manganese or appreciable percentages of chromium or nickel. The precipitation is apparently associated with decreasing solubility of some constituent in ferrite with decreasing temperature, similar to the precipitation reactions in aging some nonferrous metals. This action results in brittleness induced by the tempering operation, either at tempering temperature or during cooling, and is known as *temper brittleness*.

7.30 SURFACE HARDENING

Many parts used in industry must have a hard, wear-resisting surface and a soft, ductile core. Sometimes this soft core is desired to facilitate forming or machining operations, sometimes for impact resistance during service. For such a combination of properties, it is not feasible to harden and quench a high-carbon steel to obtain surface hardness, particularly when the hardness may be required on only a small area. Two other methods make possible such surface hardening. When the full surface is to be hardened, a method known generally as *case hardening* is usually employed. In it, the surface is impregnated with carbon or some other hardening agent to give, through quenching, a hard surface. The hardenability of the core remains unchanged, and it retains its softness after quenching. Cyaniding, carburizing, and nitriding are operations of this type.

The second method, using flame and induction hardening, was developed especially for hardening small areas. A steel having the necessary hardenability is used, and it is hardened locally. Induction hardening and flame hardening are discussed in Chapter 17. Use of these methods to produce surface hardness is increasing, because of the short time in which the operation may be performed, the low costs, and the little distortion produced as compared with the furnace heating of pieces in the case-hardening methods. These advantages are especially important on large parts such as gears, or on parts processed on an assembly line.

Cyaniding. The cyanide process is particularly applicable to small parts requiring a thin, hard, wear-resisting surface. Typical parts cyanided are small gears, ratchets, pawls, pins, bushings, screws, and small hand tools. The process consists in heating the steel in a molten bath of sodium cyanide and then quenching in water or oil.

The time of heating will vary from several minutes to 4 hr, and a case depth up to 0.025 in. is obtainable.

Carburizing. Carburizing is used for heavier parts or for those that require a deeper case (up to 0.70 in.) than is normally developed in cyaniding. Two general methods, pack carburizing and gas carburizing, are in use. In the former the steel pieces, either stamped or fully machined and containing only a small allowance for finish grinding, are packed in solid "carburizing compound (mixture of crushed wood or bone charcoal and an energizer, usually a carbonate)," and heated for periods ranging from 4 to 72 hr. The heating causes the formation of carbon monoxide gas, which reacts with the iron to form carbon and CO_2. The carbon dissolves in austenite and penetrates below the surface by diffusion. Case depths of less than 0.025 in. should not be specified for pack-carburizing work.

In the gas method the pieces are heated in a furnace having an excess atmosphere of hydrocarbon gas and carbon monoxide. The gas can also be obtained by employing a volatile hydrocarbon liquid. The same action takes place as in the pack method, but is faster, cleaner, and permits better control of the depth of the hardened area. With either method the pieces have a surface carbon content ranging from 0.8 to 1.4 C. They are reheated to a temperature somewhat lower than that used in carburizing, then quenched in oil or brine to develop the required hardness. A preliminary higher-temperature quench may be used to refine the grain of the core if it has grown too much during the carburizing cycle.

Surfaces can also be decarburized if they are heated in a hydrogen atmosphere. Where this treatment is purposely employed, promotion of surface softness is usually not the direct purpose. Decarburization is sometimes used to decrease carbon content of silicon steel sheet for motor applications.

Nitriding. Whereas almost any type of plain, low-carbon steel, or low-carbon alloy steel may be carburized or cyanided, a steel containing a nitride-forming element (e.g., Cr, Al, Mo, V) is required for nitriding. The process consists in heating the parts in a sealed container, through which is passed a stream of ammonia gas. The usual temperature is 1000 F, and the time cycle may range from 8 to 96 hr. The nitrided case may be up to 0.030 in. in depth, longer time being necessary for the heavier case. It is by far the hardest case produced by any of these processes. An advantage of nitriding is that distortion is reduced to a minimum. This is because of the

low temperature used; and, because the parts are cooled slowly, no quenching is needed.

Besides the hardness and excellent wear resistance obtained, the surface has good resistance to corrosion by alkalies, crude oil, tap water, salt water (not in motion), ethyl gasoline, and other media, and retains its hardness at elevated temperatures. The process is relatively costly because a special steel must be used, the equipment is expensive, and a long time cycle is required.

Case Hardening Small Areas. When it is desired to case harden only part of the surface, those areas which are to be soft may be protected by a metal plating. Copper plating is the correct protection for the cyanide and carburizing processes, and tinning or nickel plating should be used to oppose nitriding.

Case Depth. In the literature, case depth is usually reported as the *total* observed by metallographic methods. This often leads the designer or shopman to believe that he can grind to almost the full case depth and still have uniform hardness or wear resistance. Such is emphatically not true. For example, cyanided parts should not be ground over 0.003 in. per side, no matter how deep the case is. On carburized parts the depth of "effective," or useful, case will average about half the total. Nitrided parts should be finish ground, polished, or lapped only deep enough to remove the "blush" or frosty deposit on the surface.

Boron and silicon can be impregnated in low-carbon steel surfaces by processes similar to carburizing. The processes are known respectively as boriding and siliconizing (Ihrigizing), and both result in very hard wear-resistant surfaces.

7.31 PLAIN CARBON STEELS

Plain carbon steels constitute about four-fifths of the steel produced. They are cheaper than the alloy steels and consequently are used wherever their properties are adequate. The properties range from very soft to very hard, and these steels are suitable for a large proportion of industry's needs.

It is convenient to divide the carbon steels into two groups. One is the so-called free-cutting steels. The second is the remaining plain carbon steels not especially selected for their machinability.

The free-cutting steels consist of the three Bessemer grades B1111, B1112, and B1113, which differ mainly in sulfur content, and of the resulfurized open-hearth steels from C1108 to C1151. It is the high sulfur in these grades that promotes machinability in bar or plate

and aids wear resistance in some applications. Where loading is not heavy or rapidly repeated, Bessemer or resulfurized open-hearth steel is satisfactory. Screw stock, sheets, tin plate, tubing, pipe, concrete reinforcing, and lightweight rail are commonly made of these steels. The high sulfur and phosphorus make these steels unsatisfactory for many applications, however. They have poor welding characteristics, have low ductility and malleability, are poor in fatigue, and tend to be both hot short and cold short, making them brittle under impact loads.

The second group consists of the basic open-hearth steels from C1006 to C1095. They have higher purity and are preferred for heavy rails, structural shapes for buildings and bridges, boiler plate, drawing sheet, rivets, springs, shafts, axles, gears, and high carbon tools. Typical uses for wire, bar, plate, and sheet, or strip of these grades depends on the carbon content. Table 7.7 lists typical applications for the various levels on carbon content.

With the exception of carburizing and intermediate annealing of cold-worked material, low-carbon (under 0.30 per cent C) steels are seldom heat treated. Medium-carbon steels (0.30 to 0.70 per cent C) are frequently heat treated for hardening, improving ductility, or machinability. The high-carbon steels (0.70 per cent C and above) are almost always quenched and tempered, because typical applications for these grades require high hardness. Both the medium carbon and high-carbon steels are shallow hardening. That is, martensite forms only to the depth of the section which can be quenched past the "gate" of the T-T-T curve in a second or less. The larger pieces may develop only mixed ferrite and cementite, even at the surface, because of the low rate at which the large amount of heat in the volume of material can be removed from the surface.

7.32 LOW-ALLOY STEELS

The first investigations on the effect of alloying elements in steel were made from 1875 to 1890. But the use of alloyed steels found little application until 1910, when reduced costs of alloys made their use practicable. The stimulus of creating materials for military requirements in the two world wars which have followed greatly aided their development. Even more important, perhaps, has been the development and use of these steels for automobile applications, and later for airplanes, locomotives, machine tools, and other high efficiency products.

Table 7.7 Typical Uses for Plain Carbon Steels

Carbon Level, per cent	*Typical Uses*
0.05–0.07	High-ductility wire.
0.07–0.15	Rimmed steel is used for sheet, strip, rod, and wire where excellent surface finish is required, such as body and fender stock, panels, deep-drawing strip, steel for lamps, hoods, sectors, pawls, clutch and transmission covers, oil pans, and a multitude of deep-drawn and formed products. It is also used for cold heading wire for tacks, rivets, and low-carbon wire products.

Killed steel should be used in preference to rimmed steel for carburized parts, especially where both the rim and the core of rimmed steel are involved in the heat treatment. In the process of "rimming in," practically all the carbon is transferred from the outer part of the ingot for a depth of several inches, to the inner part. A cross section of the ingot or of any shape rolled or forged from it, will have an outer layer of almost pure iron and a core in which carbon has concentrated correspondingly. If the part to be carburized has been forged or machined in such a manner as to bring both the rim and the core metal into the case, irregular distortion may be expected.

These steels are of low tensile values and should not be selected where much strength is desired. Cold drawing or rolling improves their hardness and strength about 20 per cent over the properties in the hot-rolled condition. All the properties acquired by cold working are, however, lost when these steels are heated to temperatures of 1000 F or higher.

These steels, being ferritic in structure, do not machine freely and should be avoided for nuts, cut screws, and operations requiring broaching or smooth finish on turning. Cold drawing, however, improves their machinability.

The higher manganese varieties have improved machinability and hardening properties.

0.08–0.18	Boiler plate, seamless, weldable boiler tubes, and ship plate.
0.15–0.20	Standard carburizing grades for wrist pins, camshafts, drag links, clutch fingers, sheet and strip for fan blades and welded tubing, and numerous forged parts where high strength is not essential.

This steel may be brazed, butt welded, and drawn into various shapes but is not as desirable for deep drawing operations as 1008 and 1010. It shows some improvement over SAE 1010 in machining but is not recommended for smooth threading, turning, or broaching.

The higher manganese variants improve machinability and hardening properties. These steels carburize and harden freer from soft spots than 1020.

Table 7.7   Typical Uses for Plain Carbon Steels (Continued)

Carbon Level, per cent	Typical Uses
0.20–0.30	Small forgings, crank pins, gears, valves, crankshafts (0.20–0.26), railway axles (0.23–0.30), crossheads, connecting rods, rims for turbine gears, armature shafts in general (0.24–0.32) and fishplates. They have fair machining properties for threading, broaching, and turning. Forgings usually machine better without annealing or in the normalized condition.
0.35–0.45	Axles, special-duty shafts, connecting rods, small and medium forgings, cold upset wire and rod, machinery steel, spring clips, solid turbine rotors, rotor and gear shafts, armatures for turbo-generators, key stock, shift and brake levers, forks, and anchor bolts. They possess fair machining properties and deep hardening characteristics.
	The higher manganese variants are used for larger sections or where higher properties are desired.
0.45–0.55	Parts to be subjected to shock and heavy reversals of stress. Railway coach axles, crank pins on heavy machines, larger-size forgings such as crankshafts, starter ring gears, axles, spine shafts, and for hard-drawn wire for tempered and patented springs. Caution should be used in water quenching this steel in parts of small diameter or thin sections.
0.60–0.70	Drop-forging dies, die blocks, bolt-heading dies, plate punches, set screws, self-tapping screws, snap rings, valve springs, cushion springs, clutch springs, lock washers, spring clips, clutch discs, thrust washers, and parts for agricultural purposes, such as frogs and standards.
0.70–0.80	Cold chisels, pick axes, wrenches, jaws for vises, shear blades, hack saws, pneumatic-drill bits, wheels for railway service, wire for structural work, automatic clutch discs, mower sections, plow beams, etc.
0.80–0.90	Railway rails, plow shares, rock drills, circular saws, machine chisels, punches and dies, lock pins, clutch discs, leaf springs, music wire, mower knives.
0.90–1.00	Punches and dies, springs, balls, keys, pins, leaf and coil springs, harrow and seed discs.
1.00–1.1	Railway springs, machine tools, mandrels, springs, taps.
1.1 –1.2	Taps, tools, thread metal dies, twist drills, knives.
1.2 –1.3	Files.
1.3 –1.5	Dies for wire drawing, paper knives, and tools for turning chilled iron.
1.5 –1.6	Saws for cutting steel and dies for wire drawing.

Today there are hundreds of varieties of low-alloy steels. Compositions occasionally involve only 1 or 2 alloying elements other than carbon, but varieties with 5 or more alloying elements are not uncommon. The alloying elements, when present, are limited to the ranges shown in Table 7.5 for steels of this class.

Effect of Alloying Elements. The alloying elements are usually added for the purposes listed in Table 7.8. Note that each element does not make a steel better in every respect. Each tends to improve some characteristics at the expense of others. The elements utilized are therefore balanced in the composition to achieve a desired combination of properties. Since the alloying elements cost considerably more than the basic steel, alloyed steels are used where they provide one or more clear-cut advantages over plain carbon steels.

There are two broad classes of these steels. One class is known as low-alloy structural steel. The other is the AISI grades already mentioned.

Low-Alloy Structural Steel. There are about thirty of these grades. As a group, they contain 0.30 per cent or less carbon, 1.7 per cent or less manganese, 1 per cent or less silicon, 0.3 to 2.0 per cent nickel, 0.1 to 1.5 per cent copper with less than 0.4 per cent molybdenum, 1.5 per cent chromium, and 0.05 to 0.2 per cent phosphorus if the latter three are present. They were developed to provide a high yield-strength low-cost steel which that had good weldability, ductility, and impact strength, and better corrosion resistance than low-carbon steels. The low carbon aids weldability and assures that these steels will not air harden after welding or hot rolling. They are usually employed without heat treatment. Typical mechanical properties are: minimum hot-rolled strength of 50,000 psi, tensile strength 70,000 to 90,000 psi, and 18–30 per cent elongation in 8 in. Although the first application was for bridges, other uses have developed for railway rolling stock, trucks, buses, cranes, shovels, and similar structures.

AISI Low-Alloy Steels. These steels are widely used in automobile, machine tool, and aircraft construction, especially for moving parts subject to high stresses. They are more costly than the structural class and are therefore almost always used in the quenched and tempered condition to take full advantage of the alloying additions. In this condition they have, as a class, 30–40 per cent higher yield strength, 10–20 per cent higher elongation in 2 in., 30–40 per cent higher reduction in area, and often twice the impact strength of plain carbon steels of the same tensile strength and hardness. Since they are also deeper hardening than the plain carbon steels, they can be

Table 7.8   Effects of Alloying Elements * Upon Properties of Steel

	Carbon 0.10–0.30	Carbon 0.31–eutectoid	Effect of Single Alloying Element upon Low-Carbon Steel (0.1–0.6 C)								
			Mn 0.25–2.00	P 0.0–0.15	S 0.0–0.3	Si 0.0–2.0	Cr 0.0–1.1	Ni 0.0–5.0	Mo 0.0–0.75	V 0.0–0.25	Cu 0.0–1.1
Hot working	+2P	−7P	+7S	0	−10S	−5P	0	−6P	−3P	0	−10S
Cold drawing	−4P	−10P	−10P	−10P	−10P	−10S	−10S	−10S	−10P	x	−10P
Cold bending	−2L	−10P	+2I	−10L	−7P	−6P	−10P	+5S	+3S	+3P	+2P
Machinability †	+2P	−2P	−6P	+6P	+10P	−2P	−2P	−10P	−5P	0	x
Weldability	−2L	−10P	−10L	−7L	−3P	−5L	−10L	−10L	−10L	+1P	−4L
Hardenability (depth)	+1P	+2P	+10P	+3P	−2P	+2S	+7S	+10L	+7S	+5I	xx
Strength †	+4P	+10P	+5P	+5P	−2P	+7P	+5P	+5P	+5P	0	+1P
Creep resistance	+2I	−3P	0	0	0	0	+1P	0	+10P	?	?
Toughness †	−3P	−8P	+2I	−8P	−6P	−2P	−8P	+10P	+3S	+2P	+1L
Low temp, toughness †	−3P	−10P	+2I	−10S	−6P	−1P	−10P	+10S	+3S	+3P	x
Corrosion resistance	−3P	−6P	0	+10P	−10P	+2P	0	+6L	+2P	0	+10S
Wear resistance ‡	0	+10P	+6P	+1P	0	+2P	+8P	+3L	+5P	+2P	xx

Key

Number indicates relative magnitude of effect.
+   Improvement in property.
−   Reduction in property.
P   Effect is proportional to quantity of alloying agent.

S   Small quantities most effective.
L   Large quantities most effective.
I   Intermediate quantities most effective.
x   Probably negative.
xx   Probably positive.

* From data by Mr. John Mitchell in *Contributions to the Metallurgy of Steel*, Am. Iron & Steel Inst., by permission of the author and publisher.
† As rolled.
‡ Fully hardened.

LOW-ALLOY STEELS

hardened through thicker sections; or less drastic quenches, producing less distortion and stress, may be employed for equivalent sections. When given the same heat treatment, tensile strength may differ by as much as 50,000 psi for these grades. But when heat treated to
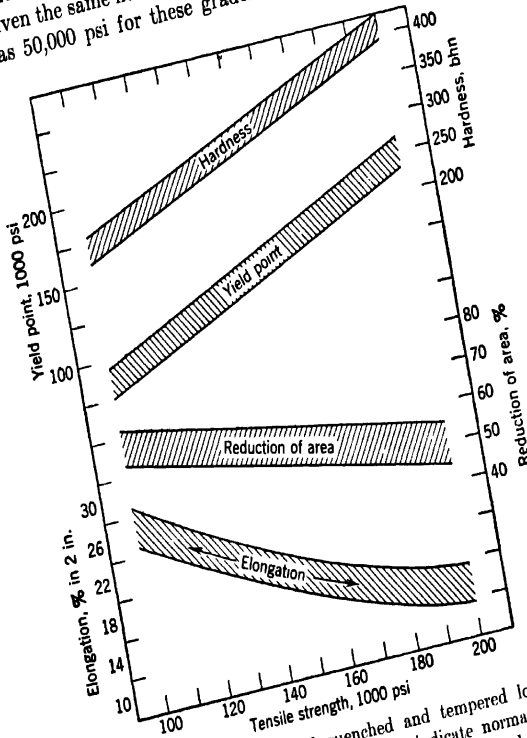
FIG. 7.35. Mechanical properties of quenched and tempered low-alloy steels containing 0.30 to 0.50 per cent carbon. Bands indicate normal variations in indicated properties. Note that these properties are equivalent for various grades if they are heat treated to the same tensile strength.

produce the same tensile strength and hardness, all steels of this class have approximately the same yield point, reduction of area, and elongation (see Fig. 7.35), provided tensile strength is below 200,000 psi. Above this value there is some scatter, particularly in endurance ratio and in impact strength, which may vary more than 20 per cent, probably because of stresses induced by the drastic quench required for some grades.

The manganese steels of lower-carbon content are particularly

adapted to carburizing and direct quenching from the furnace. The higher-carbon contents are used interchangeably with equivalent plain carbon steels with advantages in lower quenching rates for the same properties.

Nickel is usually added to a low-carbon steel, because it is more easily dissolved by the ferrite than cementite. The dissolved nickel increases toughness, hardness, resistance to galling, checking, and fatigue failure, the elastic limit, and the elastic ratio. In addition, the grain structure is refined, creep at high temperature is reduced, heat treatment and casting are aided, and case hardening is not impaired.

Nickel-chromium steels are used where greater strength, toughness, and hardenability are desired than can be obtained with lower-alloy contents. The low-carbon grades are suited to carburizing for parts like gears, pinions, crankshafts, and piston pins. The medium-carbon grades are used for shafts, links, studs, and bolts where properties are obtained by water quenching. The high-carbon grades of this class (0.40–0.50 per cent C) are used for forgings and machined parts where properties are obtained by oil quenching. Typical grades and uses are given in Table 7.9.

Table 7.9   Typical Uses for Nickel-Chromium Low-Alloy Steels

Nickel, per cent	Carbon, per cent	Typical Uses
0.4 to 0.6	0.10–0.20	Pinion gears, rear-axle differentials, case-hardened parts with little distortion.
1.0	0.40	Good forging material for automobile front axles, etc.
1.5	0.15	Engine bolts, rivets.
2.0	0.20	Large-frame castings, steel-mill machinery, ship castings, and castings subjected to shock and fatigue. Boiler plate for locomotives, and fire box plate and tubes.
2.75	0.15	Locomotive forgings, piston rods, side rods, main rods, and axles.
3.25 to 3.75	0.15	"King" pins, piston pins, roller-bearing races, universal joints, and spring clips.
3.25 to 3.75	0.40	Drive shafts, and other heavy splined shafting.
3.25 to 3.75	0.50	Connecting rods. Tube in this class is used for bearing races, collars, valve seats, cylinder liners, stressed rings, etc.
4.5 to 5	0.50	Transmission gears on trucks and heavy apparatus.

Molybdenum steels, the C4XXX AISI Series, offer still higher mechanical properties with less drastic heat treatments. The carburizing grades contain up to 0.25 per cent carbon. Higher-carbon grades (0.40 and above) are oil hardening and are used as alternatives for alloys of lesser alloy content and similar carbon content, particularly in heavier sections where the advantage of their reduced distortion and higher hardenability is important.

Chromium steels of the C51XX Series are deep hardening and suited to oil quenching. They, too, are used interchangeably with alloys of similar carbon content where their hardening characteristics are important. The 5X100 Series are used chiefly for ball or roller bearings and races; they have deep-hardening characteristics, and high hardness is developed.

Chromium-vanadium steels, the 6XXX Series, are suited to heat-treated machine parts and heavy forgings, where still higher strength and fatigue properties are required than are available in the previous alloy steels.

The nickel-chrome-moly steels of the 8XXX and 9XXX Series were originally developed as lower strategic alloy replacements for the previous alloys containing similar elements, particularly for heat-treatable alloys in relatively heavy sections.

7.33 HARDENABILITY

The selection of one grade of low-alloy steel over another, and particularly of a variety of tool steel, often depends on the required hardenability. This characteristic is a measure of the severity of cooling conditions necessary to avoid transformation in the pearlite and bainite ranges on continuous cooling. The lower the rates of cooling necessary to prevent formation of pearlite, bainite, or proeutectoid products, the greater is the hardenability. Since the pearlite, bainite, ferrite, and carbide reactions are controlled independently by the alloying elements, there is a hardenability associated with each. Pearlitic hardenability, for example, is a measure of the severity of the cooling conditions necessary to avoid pearlite formation. Similar specific cooling conditions for bainite hardenability and for ferrite or carbide hardenability are required to avoid forming bainite and proeutectoid products respectively. Of these three the hardenability that is smaller provides the minimum cooling condition required for martensite to form.

There is some doubt concerning the distinction between the pearlitic and the proeutectoid hardenabilities and their relative importance.

T-T-T curves indicate the proeutectoid products should form first, except for steels close to eutectoid composition. Measurements suggest, however, that pearlite forms first on continuous cooling. Since it is not known whether small amounts of proeutectoid products affect the mechanical properties of tempered martensite, a distinction between them is usually not drawn.
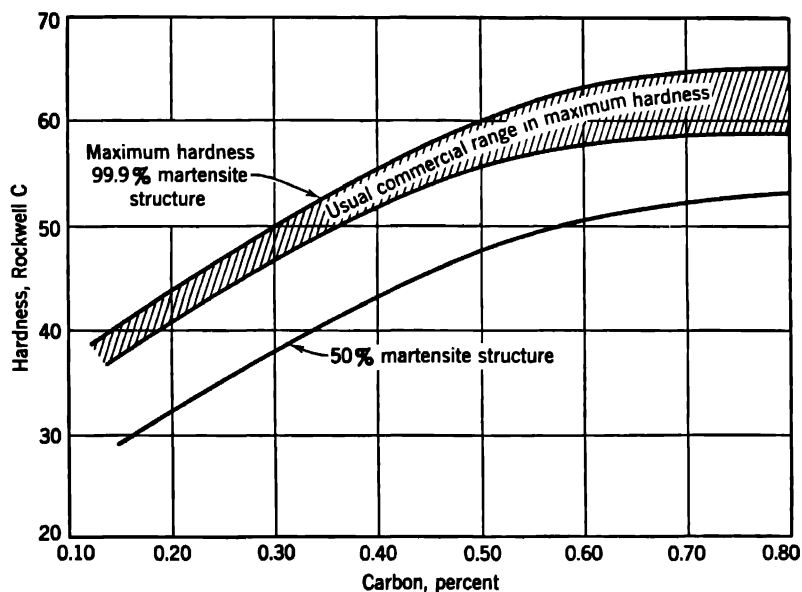
FIG. 7.36. Relation of carbon to the hardness of plain carbon steel. Data apply approximately to low and medium alloy steels. (*Metals Handbook, 1948 edition, p. 497.*)

Variables Affecting Hardenability. The main variables that affect hardenability are the alloying elements present, the grain size of the steel, the homogeneity of the starting steel, and the homogeneity obtained in the austenite before quenching.

Carbon is the primary hardening element in steels. The "potential" maximum hardness that can be developed is practically unaffected by alloys, and depends almost entirely on carbon. Fig. 7.36 shows the relation of carbon to the hardness of steel. The upper curve indicates hardness for 100 per cent martensite. This is seldom achieved in commercial practice, and values of 5 to 10 Rockwell C less are generally considered full hardness. The median line is for a hardness with 50 per cent martensite and 50 per cent pearlite, which is often called half

hardening. It applies, of course, only to steels that do not develop bainite in transformation.

Grain size, too, has an important influence on hardenability. Since the transformation of austenite begins principally at the grain boundaries, small grain size increases the likelihood of early transformation. Thus, small grain size decreases hardenability. In general, the effect of grain size is most pronounced just below the equilibrium-transformation temperature, and therefore influences pearlitic hardenability to a greater extent than bainitic. The ease with which grain size can be controlled suggests that large grain size would be advantageous in improving hardenability of shallow-hardening steels. The disadvantage of this practice is that the coarse-grained steel is liable to cracking on quenching, and has low impact strength at room temperature. For highly stressed parts, steels are maintained of fine grain size, and deep hardening is secured by alloying additions.

Lack of homogeneity exerts an influence on hardenability through premature transformation in segregated areas according to local composition, and through spread of the transformation over the whole section. Thus the effect of segregation and incomplete austenitization is to produce reduced hardenability.

Hardenability Measurements. Some indication of hardenability has been obtained by taking hardness measurements across the diameter of a bar subjected to a given quench. Repetition with bars of different size enables plotting curves like Fig. 7.37. Such curves
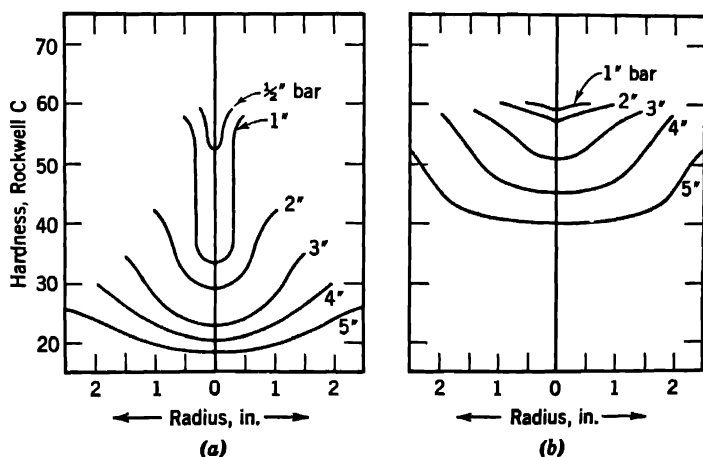
Fig. 7.37. Hardness versus cross section for hardened bars of various diameters. (a) SAE 1045 quenched in water. (b) SAE 4140 quenched in water.

clearly show that the 4140 steel is *deeper hardening* (or *hardens through* to a greater extent), under a given quench, than 1045 steel. The latter hardens through for a ½-in. bar but is *shallow hardening* on thicker bars. Since this method involves considerable testing time, and must be repeated for each different quench, it is giving way to the Jominy method.

In the Jominy test for hardenability of steel, a sample approximately 1 in. in diam and 4 in. long is heated to the proper temperature and then quenched on one end by means of a standardized "fountain"
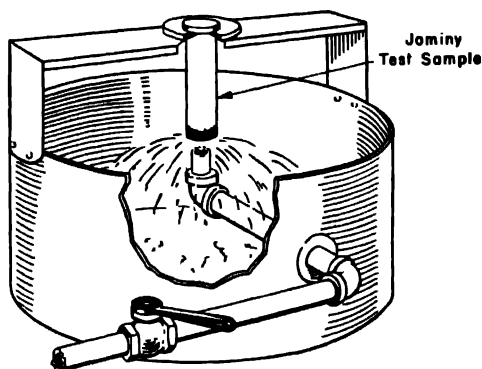
Fig. 7.38. Sketch of Jominy end-quenching operation. (*Courtesy of Joseph T. Ryerson & Sons.*)

of water, as illustrated in Fig. 7.38. This produces very rapid cooling on the quenched end, with progressively slower cooling along the bar. The rates of cooling at different points have been carefully determined and are given in Fig. 7.39.

After quenching, two flats are ground lengthwise on the bar, and indentation hardness readings taken at measured distances from the quenched end (see Fig. 7.40). The hardenability specifications mentioned in paragraph 7.22 are of this form, two curves being used. One establishes the high values, the other the low, thus forming a band of hardness to be achieved in the Jominy test.

Comparison of hardness readings on the Jominy bar with the rates of cooling, given in Fig. 7.39, makes it possible to ascertain the hardness that would be obtained in a section of a part made of the same material and cooled at some specified rate. Conversely, if the hardness of the material of some part is known, the cooling time can be determined by reference to Jominy tests for the material. It is also possible, on the basis of these tests, to select a material that will

have the proper gradient of hardness for the cooling times given by
a quench, e.g., in water or oil, by plotting the desired Jominy hard-
ness curve and comparing it with the curves for the available alloys.

The Jominy test can be made relatively quickly and cheaply, and
agreement between various laboratories has been good. In addition,
the agreement between results on cast and rolled sections has been
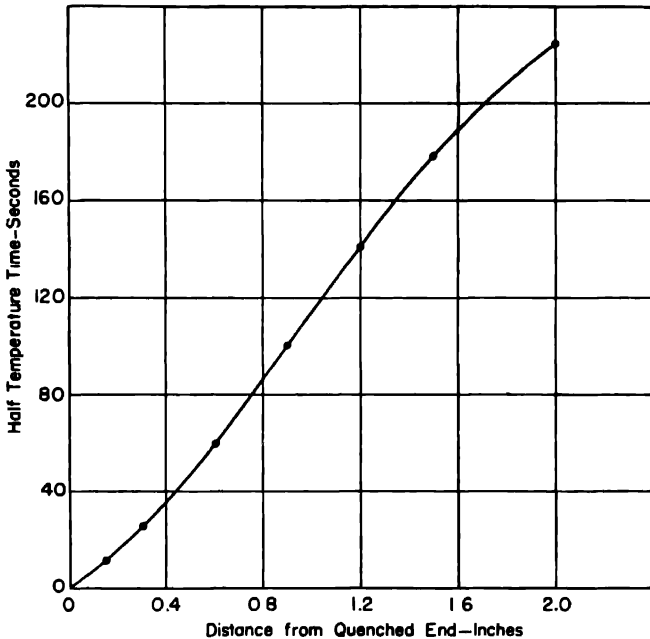
Fig. 7.39. Cooling rates on a Jominy test bar expressed as half temperature
time. (*From Correlation between Jominy Test and Quenched Round Bars, by
Asimow, Craig, and Grossman*).

good for plain carbon and low-alloy steels, and is about 5 Rockwell C
lower for cast deep-hardening steels than for wrought. This enables
use of the test prior to rolling a batch of steel at the mill to deter-
mine ability to meet hardenability specifications.

There are some disadvantages. Presence of pearlite is indicated
by hardness measurements, but presence of bainite is not. Therefore,
bainite structures may be present with consequent influence on prop-
erties. Steels that are segregated or otherwise not homogeneous will
have large deviations from a Jominy bar result. Steels subjected to
a large amount of work may differ from cast bar Jominy test. And
finally, a great deal of internal stress may affect transformation rates

and introduce error in interpreting a Jominy bar test for properties in parts of, say, 2 in. diam. These factors must be considered if Jominy tests are to be applied accurately.

Hardenability Calculations. In 1942 Grossman reported * that the hardenability of most plain carbon and low-alloy steels could be predicted from its chemical composition, provided the grain size was known and the austenite was homogeneous before quenching. His data applied to pearlitic hardenability and assumed that the funda-
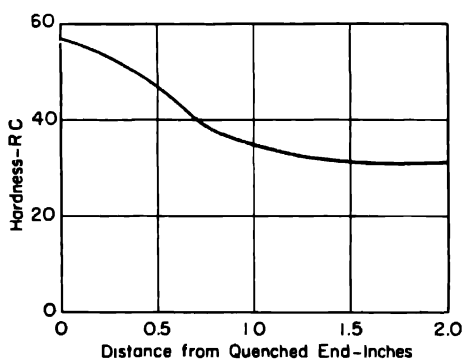
FIG. 7.40. Jominy hardness for NE 9440 alloy steel. (*Courtesy of Joseph T. Ryerson & Sons*)

mental hardenability due to carbon alone may be multiplied by factors for each alloying element present to determine actual hardenability. Grain size was taken into account either by choice of fundamental hardenability or as a final multiplication factor. The method further based hardenability on a bar of *ideal diameter* which was defined as the diameter of a bar which would harden to 50 per cent martensite and 50 per cent pearlite at the center when subjected to an *ideal quench.* Using experimentally determined factors for the effect of each alloying element, the ideal diameter is calculated. This diameter is then corrected † to the diameter of an actual bar which will harden to 50 per cent martensite at the center in a specific quenching medium.

Utilizing correlations worked out by Field,‡ the Jominy bar hard-

* M. A. Grossman, *Trans. Am. Inst. Mining, Met. Engrs.,* Vol. 150, 1942, pp. 227–259.

† Sisco, F. T., *Modern Metallurgy for Engineers,* Pitman Publishing Co., New York, p. 274.

‡ Joseph Field, *Metal Progr.,* Vol. 43, 1943, pp. 402–405.

ness-vs.-distance curve (like Fig. 7.40) can be calculated for a given steel. From composition and grain size, Grossman's ideal diameter is first calculated. The hardness at the water-cooled tip of the bar is assumed at full commercial hardness (Fig. 7.36). Values for hardness at various distances along the bar are determined by multiplying the end hardness by a factor obtained from a plot of ideal diameter vs. factor for several Jominy distances.* It is claimed this method gives calculated Jominy curves within 1 to 2 Rockwell C of actual test values for plain carbon and low-alloy steels other than those containing less than 0.25 to 0.30 per cent carbon.

An extension of these methods has been made by Hollomon and Jaffe,† who present factors for calculating the pearlitic hardenability and the bainitic hardenability in terms of an ideal round (ideal diameter) and for either full hardening (95 per cent martensite) or half hardening (50 per cent martensite). Values of ideal rounds for all the *SAE* and *NE* median compositions are determined together with numerous charts relating quenching of plates, bars, and tubes in various media to the Jominy bar or to the ideal round with ideal quench. With these data the ideal round for pearlitic and bainitic hardenability can be determined, for full or half hardening at the center, whichever is of interest. The smaller ideal round determines which hardenability is limiting, pearlitic or bainitic. The curves for the actual shape and cooling medium then permit determination from the minimum ideal round the maximum actual diameter that results in the center hardness selected.

7.34 TEMPERABILITY

The use of tempering treatments to induce a controlled precipitation of carbides in martensite, and a resulting combination of strength and toughness, has been mentioned. The characteristic response of a steel to tempering for these purposes is known as *temperability*.

In steels where alloy carbide-forming elements are absent, no retained austenite is present, and the composition is not susceptible to temper brittleness; the time and temperature necessary to produce a given hardness are then related. The degree of tempering can be expressed by a single parameter, covering the effects of time and temperature used. Such a relationship is illustrated in Fig. 7.41.

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* Sisco, F. T., *Modern Metallurgy for Engineers,* 2nd edition, Pitman Publishing Co., New York, 1948, p. 276.

† Hollomon, J. H., and L. D. Jaffe, *Ferrous Metallurgical Design,* John Wiley & Sons, New York, 1947.

If retained austenite is present, the low-temperature tempering products may not be the same as those obtained with high temperature and shorter time. The hardness may not be greatly affected after tempering, but impact properties may be widely different.

The temper-brittleness transformation does not have the same time-temperature relationship for tempering as for ordinary precipitation of carbides. Above 1100 F, temper-brittleness precipitation
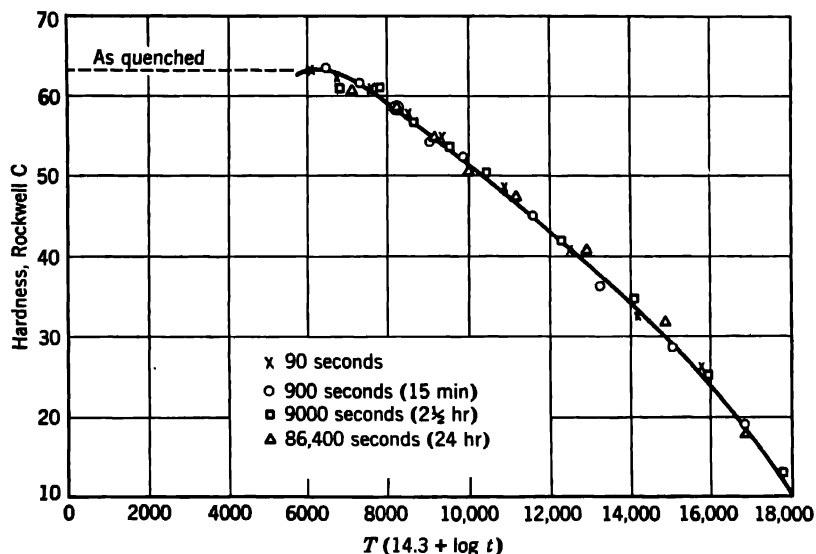
FIG. 7.41. Temperability of plain carbon steel. (*Hollomon and Jaffe.*) $T =$ absolute temperature, $t =$ time.

does not occur. Below this temperature the transformation has a "C" shaped curve to temperature vs. time. Therefore, tempering a susceptible steel above 1100 F will not result in loss in toughness evident at lower temperatures, even though hardness may be the same.

Tempering of alloys that contain carbide-forming elements does not result in continuously decreasing hardness with increased parameter of temperature vs. time. Instead, the higher tempering temperatures (and long tempering times) induce the formation of alloy carbides that retard the softening. They often cause hardness to increase with temperature or time over a limited range (see Fig. 7.42), a characteristic termed *secondary hardening* and similar to precipitation aging of nonferrous alloys.
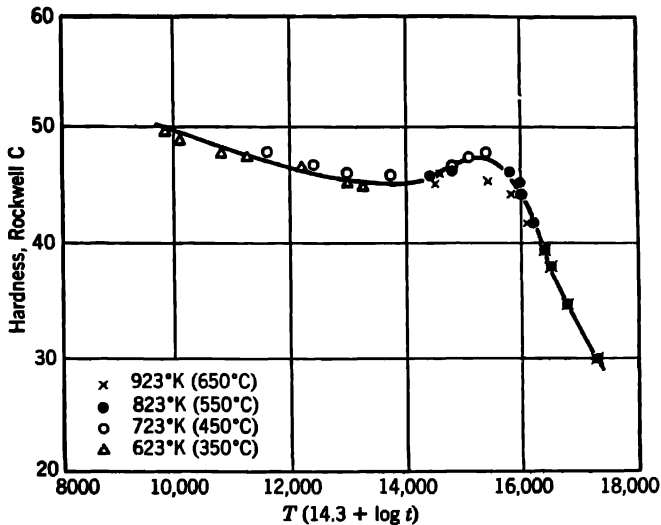
Fig. 7.42. Temperability of a carbide-forming steel. Secondary hardening is evident at $15{,}000 = T(14.3 + \text{Log } t)$. (*Hollomon and Jaffe.*)

The primary effects of specific alloying elements on the constitution diagram, on hardenability, and on temperability of steel are briefly summarized in Table 7.10.

7.35 HIGH-ALLOY STEELS

There are four general classes of metals applications which utilize the highly-alloyed steels. They are: (*a*) the well-known tool steels and the closely associated valve and die steels; (*b*) steels having high corrosion resistance; (*c*) steels having high scaling resistance and/or high mechanical properties at high temperatures; and (*d*) specialized purpose steels for magnetic, electrical, wear-resistant, or other special properties. Steels typical of these classes are briefly mentioned in the following paragraphs.

Tool and Die Steels. These steels are used for cutting tools, shearing tools, forming dies, and battering tools. Hardness, strength, toughness, wear resistance, and in some cases resistance to heat softening are the properties of importance in selecting steels for these applications. A number of different types of steel are used, depending on the combination of conditions to be met.

Plain carbon steels harden with a hard case and a softer core, except in small sizes, and these properties are suited to a number of applications. Hot-forming and heading dies, hammer heads, and

Table 7.10 The Effect of Alloying Elements in Steel (on the Basis of Weight Percentage)

Effect	Decreasing A_3 Temperature	Decreasing M_s Temperature	Increasing Hardenability		Increasing Temper Brittleness	Increasing A_{cm} Temperature	Carbide-Forming Tendency	Increasing Tempered Hardness	
			Bainitic	Pearlitic				No secondary hardening	With secondary hardening
Stronger positive effect	C	C	C	C	Mn	Ti	Ti	C	V
	N	Mn	Mn	Mn	Cr	C	V	Mn	C
	Mn	V	P	Mo	Ni	V	Mo	Si	Mo
	Ni	Cr	Cr	P		Mo	W	Mo	Cr
	Zn	Ni	Si	Cr		W(?)	Cr	Cr	Mn
	Cu	Cu	Ni	Si		Cr	Mn	Ni	Si
	Cr(?)	Mo	Cu	Ni		Si		Co	Ni
		W	Mo	Cu		Mn		V(?)	Co
						Ni(?)			
						Cu(?)			
No effect	Co	Si	Co(?)	Co	W(?)		Ni		
	W	Co			Mo		Si		
	Mo	Al							
	Si								
	V								
	Sn								
	Al								
Stronger negative effect	Be								
	P								
	Ti								

rivet sets are made from grades with 0.60 to 0.75 per cent carbon; chisels, shear blades, smithing tools, swages and flatteners from 0.75 to 0.90 per cent C; hard chisels, large taps, trimming dies, drills, milling tools, threading dies, blanking, forming drawing dies and punches from grades having 0.90 to 1.1 per cent C; and small taps, reamers, planing tools, woodworking tools, and razors from grades having 1.10 to 1.40 per cent C.

Pneumatic chisels, rivet busters, coverete breakers, and heavy-duty punches, etc., are applications involving higher shock resistance than is available in the 0.75 to 0.90 per cent carbon steels. Steels used for these applications are of the medium-alloy type and include chrome-vanadium, low-silicon-manganese, high-silicon-manganese, and chromium-tungsten "shock-resisting" steels.

So-called "high-speed steels" are of compositions that have very good wear resistance and retain their hardness at high temperatures. They are used in simple shapes, where their distortion and moderate susceptibility to cracking during heat treatment are not limiting. The general-purpose grades are either of the high-tungsten or high-molybdenum type. The former contains 18 per cent tungsten, 4 per cent chrome, and 1 per cent vanadium. Higher vanadium contents to 3 per cent improve abrasion resistance and make these steels suited for tools for fine cuts, like broaches and reamers. The 4.5 per cent molybdenum, 6 per cent tungsten, 4 per cent vanadium, and 4 per cent chrome grades have similar uses. Cobalt additions from 5 to 12 per cent in both types increase high-temperature hardness and abrasion resistance. The cobalt-tungsten grades are used for heavy-duty tools for heavy cuts. The cobalt-moly grades are especially used for cutting gritty, scaly material such as sand-cast alloys or heat-treated steels. Since these tool steels are more brittle than the other grades, they are not recommended for tools for finishing cuts.

Die operations such as forging, coining, sheet and wire drawing, cold heading, die and permanent-mold casting, and plastic molding make use of a number of different steels. Choice depends on the temperatures involved, need for abrasion resistance, and the amount of production expected from the die set. Some of the tool steels already mentioned are used where their strength, toughness, and "red" hardness suffice. For higher "red" hardness, a group of steels known as *hot-working tool* steels are available. They are medium to high C, medium Cr steels with vanadium, tungsten, and molybdenum additions. Another group of steels, known as the "nondeforming" tool

steels, are used where design prevents use of water-hardening steels because of the hazard of distortion and cracking during hardening. These nondeforming grades include manganese oil hardening, tungsten oil hardening, chromium oil hardening, manganese air hardening, and high-carbon high-chromium steels. For review of the many types available and discussion of their applications, the reader is referred to *ASM Handbook*, 1948 edition.

The Stainless Steels. There are two general classes of stainless steels: (1) the straight chromium alloys, and (2) the chromium-nickel alloys.

The straight chromium alloys are designated in the AISI system by numbers in the 400 and 500 series. The 400 series applies to alloys with from 11.5 to 30 per cent chromium, and the 500 series to alloys with 4 to 6 per cent chromium. Some of these alloys are hardenable by heating and quenching, which forms a martensitic structure. Others, which are nonhardenable, form a ferritic structure. Both types are magnetic, are suited to cold or hot work (except high-carbon grades), are machinable, and may be welded. Welds are apt to be brittle because the martensitic types will air harden from temperatures above 1500 F as occur in welding. The ferritic types have slightly better corrosion and scaling resistance up to 1200 F, but have lower high-temperature strength. Excessive grain growth may occur under prolonged high temperature exposure of the ferritic grades, and they may show brittleness after welding, which makes them unsuited to vibration or impact service.

The chromium-nickel grades designated by AISI numbers in the 300 series usually have more than 6 per cent nickel and more than 24 per cent of nickel and chromium together. They are austenitic, nonmagnetic, cannot be hardened by heat treatment, and are well suited to cold working, hot working, and welding. Their corrosion and scaling resistance is superior to the straight chromium grades, but they are susceptible to intergranular corrosion if heated in the temperature range of 800 to 1600 F. The heating causes precipitation of chromium carbides, leaving the remaining chromium-impoverished material susceptible to corrosive attack. The condition can be avoided by reheating to 1550–1650 F to take the carbide back into solution, and then by quenching to room temperature. Additions of columbium (10 times per cent C) or titanium (4 to 6 times per cent C) will stabilize the austenitic types against carbide precipitation and thus minimize the tendency for intergranular corrosion. Grades 308, 309, and 310 have increasing contents of chrome and

nickel and increasing resistance to corrosion and to oxidation up to 2000 F (see Chapter 5).

Other alloying elements are added to these stainless steels to modify the properties. Tungsten up to 3 per cent and molybdenum up to 4 per cent are added to increase high-temperature strength. Silicon up to 3 per cent and aluminum to 3 or 4½ per cent improve resistance to scaling. Sulfur or selenium improves machinability, forming the so-called free-machining stainless steels. They are added with manganese or molybdenum as balancing components. Manganese up to 2 per cent improves hot-working characteristics. Copper from 1 to 4 per cent improves resistance to corrosion by chlorides, and nickel up to 2 per cent in the straight chromium grades improves hardenability and resistance to salt-water corrosion.

Steels for High-Temperature Use. Heat-resisting steels have as their primary properties good resistance to high-temperature creep and rupture, good oxidation and corrosion resistance, and sufficient ductility for fabricating operations. All of them contain 4 or more per cent chromium for oxidation resistance. Silicon and aluminum act similarly and are often added to enhance this resistance. Strength of carbon steels at elevated temperatures drops to low values with prolonged heating at 700 F. Additions of molybdenum, tungsten, or columbium increase strength at these temperatures up to approximately 1000 F. For higher-temperature service the ferritic steels are no longer suited, and high-chromium or high-chromium-nickel austenitic grades are used sometimes with additions of tungsten, molybdenum, and columbium to promote further high-temperature strength. Cobalt additions to the latter grades having as much as 35 or 45 per cent chrome-nickel permit still higher temperatures (see Chapter 8).

Low-Temperature Steels. It is well known that the low-carbon steels increase in tensile strength at low temperatures, but the ferritic varieties become brittle under impact at −40 F unless properly deoxidized. This characteristic becomes low at −80 F in thoroughly deoxidized low-carbon steel in the as-rolled condition. Normalized aluminum-deoxidized steels retain toughness to −100 F. In the low-alloy constructural steels, fine grain is superior to coarse grain. Small percentages of Ni, Cr, Mo, and V should be present, and rapid cooling from 1500–1600 F and tempering to 1000–1200 F gives toughness to temperatures approaching −200 F. Eight or more per cent nickel steels have high toughness to −300 F if normalized. Chrome-manganese-nickel stainless steels and the austenitic stainless steels are especially suited for service to −300 F, although the latter with Mo, Ti

or columbium have even higher toughness. Forty per cent nickel-iron alloys also retain toughness to −300 F. Some manganese alloys with small nickel or Cr also retain toughness to this temperature, but straight manganese alloys and those with 1 per cent C are limited to −100 F.

Wear-Resistant Steels. The choice of steels for their wear resistance depends principally on the nature of the contact involved, as mentioned in paragraph 4.27. In contact between steel and a nonmetal or an abrasive, the steel should be the harder material. When the abrasive is the harder, because the steel cannot achieve sufficient hardness or would be excessively brittle if so, the wear of the steel is reduced as hardness is increased. Impact conditions increase the importance of toughness in the material and absence of high residual stresses from processing.

If wear is a combination of erosion and corrosion, as in contact between steam, water, or gaseous combustion products, the choice of steel should provide hardness and corrosion resistance at the temperatures involved.

Contact between metals is perhaps the broadest application for wear-resistant steels. For such applications, the significant requirement is that the materials be *compatible.* Choice of a steel component thus depends on the mating material and on the lubrication. At low pressures with low relative velocities and intermittent operation, the bronzes of the oil-impregnated type or with greasing serve adequately with smooth pearlitic steel. Since higher speeds increase the heat generated, better lubrication is needed to maintain a film and to remove the heat, and materials resistant to the higher temperatures are required. Sulfurized Bessemer steel and permanent mold (nonpearlitic) gray iron make a good combination under light loads with pressurized lubrication. Under these conditions, the babbitt-bearing materials are also good, with plain carbon forgings and low-alloy steels. For high speed and for conditions where the lubrication cannot be counted upon to maintain separating film, higher hardnesses of both contacting materials assume greater importance. A differential in hardness should exist between the mating parts, and solid-solution compositions should be avoided. Smooth surfaces are of particular importance when pressures are high, as are high-pressure additives in the lubricant and, sometimes, additives that will develop a protective film on one of the materials. The higher-hardness steels are obtained by heat treatments, which produce high carbide content. Alloy steels with good hardenability may be hardened at the contact

surfaces by flame or induction methods (see Chapter 17). Small parts may be through hardened. Low-carbon content steels may be surface hardened by carburizing or cyaniding for light duty and by sulfiding (Ihrigizing), siliconizing, or boriding for heavier duty. Porous, hard-chromium plating and nitriding with the nitralloys or austenitic steels may also be used for moderate duty. For heaviest duty, air-hardening steels, or hard-surfacing (see Chapter 20) by welding on a surface layer with cobalt-chromium-tungsten alloys and others are probably best. Sintered carbides have a high degree of wear resistance but they are subject to chipping under impact, just as steels which are too hard and brittle may spall under impact conditions.

Nitriding Steels. The steels developed for nitriding are known as nitralloy. The commonly used grades contain 0.20 to 0.40 per cent carbon, 0.9 to 1.5 per cent Cr, 0.85 to 1.20 per cent Al, and small additions of Mo, Si, and Mn. Alloys with nickel additions may be used to obtain higher strength in case and core. The austenitic stainless steels may also be nitrided, if the oxide scale is removed by pickling prior to the operaton, but the corrosion resistance of these steels is reduced. The nitralloys are particularly suited to case hardening with minimum distortion. Stock for machined parts is generally purchased in the sorbitic heat-treated condition, but forgings are heat treated afterwards to refine grain and improve machinability. Decarburized material must be removed from heat-treated stock to eliminate brittleness and spalling tendencies of the case.

Magnetic Steels. Steels selected for their magnetic properties consist of three general groups. Permanent magnets are made from some grades of hardened steels. Electromagnet cores and magnetic circuits are made from plain carbon steels and silicon-steel sheets in the annealed condition. Structural parts in the magnetic circuit are often made from nonmagnetic (feebly magnetic) steels to reduce energy losses. The compositions used for each and their properties are covered in Chapter 6.

Special Sheet Steels. Sheet steels are subjected to temperatures from 1350 to 1600 F (usually about 1450 F) during porcelain enameling and will warp and sag considerably unless the composition and processing are carefully controlled. Enameling grade materials are specified when used for vitreous enameling applications. Typical compositions and their preparation are reviewed in Chapter 13.

Clad sheets are another special-purpose form in which steel is utilized. Tin or zinc (galvanized) plating may be applied by hot dip or electrodeposition. Coatings of lead and tin, called terne, may be

applied by the hot-dip method. Other surfacing alloys such as nickel, chromium, etc., may be applied by high-temperature rolling. These sheets make possible a fabrication that uses the lower-cost steel for its structural value and provides high corrosion protection from the clad surfaces.

7.36 CONCLUSION

It is evident from the previous paragraphs that the irons and steels available to the design engineer constitute a broad and versatile group of low-cost constructional materials. Properties are available from soft irons for baling wire to the hard steels for cutting tools and forming dies; from easily corrodible sheet to forms highly resistant to corrosion and high-temperature oxidation; and from brittle to tough over a wide range of temperatures. Sizes and commercial forms range from small rods and wire to heavy plate and castings. It may be said without exaggeration that the designer's ingenuity is challenged to apply economically and effectively these wide property ranges and these many forms.

Review Questions

1. Name the three principal constituents of the blast-furnace charge and the function of each. In what form is each when it leaves the furnace? What determines the temperature at which the various blast-furnace reactions take place?

2. Describe typical properties of the following cast irons, and indicate a typical application for each: (a) gray cast iron, (b) white iron, (c) malleable iron, (d) ductile iron, (e) alloy iron (ferritic), (f) austenitic alloy iron, (g) inoculated iron. Which is best for each of these properties: wear resistance, impact resistance, corrosion resistance, machinability, hardness, and weldability?

3. (a) How does the Aston process for making wrought iron differ from the puddling process? (b) In what applications is wrought iron used instead of steel, even though steel is often less expensive?

4. What furnace produces the largest tonnage of steel? What furnace produces the cheapest steel?

5. (a) What gives a furnace the name "acid" or "basic"? (b) What impurities are removed in the basic open-hearth furnace, and how does the acid open hearth compare in refining ability? Explain why a basic furnace lining must be used when the slag is basic.

6. In general, how does a "rimmed" ingot differ from a "killed" ingot? What sorts of products might be made from each?

7. The percentage of carbon in a steel is one of its most important specifications. For instance, plain carbon steels with 0.10, 0.40, and 1.0 per cent are distinctly different types. How do they differ in hardenability, strength, ductility, machinability, and weldability? What is a typical use for each?

8. (*a*) Give at least two reasons for adding each of the following elements to steel: molybdenum, silicon, chromium, nickel, and tungsten. (*b*) By comparison with plain carbon steel, how much alloy steel is used? (*c*) Since alloy steels possess so many advantages, why are all steels not alloyed?

9. Outline the three carbon ranges for low, medium, and high plain carbon steel, the alloy ranges of low-alloy and high-alloy steel, and describe the broad categories of materials available under each.

10. Of what operations does hardening of steel usually consist? Annealing? tempering? What is the purpose of each?

11. Describe the structural transformations which occur under continuous cooling of 0.40 per cent carbon steel at various rates. Indicate changes which occur under tempering at various temperatures to the A_{e1} temperature.

12. How are the *T-T-T* curves developed? Explain the three types of transformations indicated on them.

13. Define hardenability. How is hardenability of carbon steel affected by carbon content and grain size? In general, how do alloys affect hardenability? Which ones seem to have the greater effect?

14. How may Jominy end-quench tests be used to select a steel which will give a specified hardness gradient for a given quench, say in oil or in water?

15. What properties are usually present in fine-grained steel, as compared with a coarse-grained steel of the same composition?

16. What is normalizing? For what purpose is it employed in carbon steels having more than 1 per cent carbon? When used for medium carbon steels and followed by reheating to below the transformation temperature, what properties are obtained? What name is given collectively to these two treatments?

17. It is desired to case harden the following parts: (*a*) a small gear (very little distortion permitted, and no further machining); (*b*) a turbine valve (absolutely true shaft—no further machining or grinding); (*c*) a refrigerator crankshaft (remove 0.005 in. in finish grinding).

Indicate the case-hardening method which would be most suitable. Which would be the more expensive?

8 NONFERROUS METALS AND ALLOYS*

8.1 INTRODUCTION

Nonferrous metals and alloys include all the metals, such as copper, aluminum, magnesium, and zinc, in which iron is not present in large quantities. The total annual production of all these nonferrous metals is only one-fifteenth that of iron and steel. A comparison of the total value of finished products would show that they are considerably more important, however, since the nonferrous metals are used for parts whose finished value is high.

Many nonferrous metals, for instance the precious metals gold, platinum, etc., are used only in small quantities by industry. Many others are used only as alloying agents and are not important in their own right. Most of this discussion is directed to those nonferrous metals used in pure form or as base metals for alloys of industrial importance.

The nonferrous metals are generally used for parts requiring considerable fabrication and where the advantages gained from proper use of their characteristic properties justify their higher cost. No single property or group of properties will be the basis for every choice. But one or more of the following criteria is often involved: (1) ease of fabrication; (2) corrosion resistance; (3) electrical and thermal conductivity; (4) weight; (5) strength; (6) modulus of elasticity; and (7) color.

"Ease of fabrication" is a general term referring to casting, forging, rolling, welding, or machining properties of the material. Several of the nonferrous metals and alloys are particularly easy to cast because of high fluidity when molten, and low melting temperature. Since their melting temperatures are usually well below those of steel molds, such high-production processes as permanent mold, die, and cold-chamber pressure casting are possible with them.

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* Prepared from a previous manuscript by D. Basch, R. G. Thompson, and R. E. Moore.

Many are malleable and ductile while hot, thus permitting hot forming. Many are also easily cold formed. Some of them are difficult to machine, but special machining grades of alloys are available. Their fabrication properties vary so widely that some suitable metal or alloy can be obtained for nearly every process.

Most of the nonferrous metals resist corrosion by certain environments, but none will resist all corrosive influences. There are nonferrous metals, or combinations of them, however, which will resist nearly any particular kind of corrosive attack. Some corrosion properties are mentioned in this chapter, but more complete discussion on the corrosion of metals is given in Chapter 5.

The electrical and thermal conductivities of the nonferrous metals vary widely from very much above those of the ferrous metals to well below them. Copper is fairly inexpensive and has high conductivity, so it is used for electrical conductors. By comparison, some nickel alloys have very low conductivity, and so are used in electrical resistors (see Chapter 6).

The density of the nonferrous metals varies from one-fourth to over four-thirds that of iron. The lightweight metals, magnesium and aluminum, are used in parts for high-speed, lightweight machines, and for transportation equipment. Tungsten and lead, the heavy metals, are often used as ballast or counterweights.

On a volume basis, the strength of the nonferrous metals is generally below that of the strong steels. Compared on a weight basis, however, the strong alloys of aluminum and magnesium are as strong as the steels. The heavy nonferrous metals and alloys are never used for their strength alone because steel is stronger and less expensive.

Several of the nonferrous metals, notably the lightweight ones, have low moduli of elasticity. An aluminum beam of given rigidity or stiffness, for example, would be made with a deeper cross section than if constructed of steel; but the larger lightweight metal part would probably weigh less.

In selecting the material for architectural fittings or household equipment, the color or finish is often important. Several of the nonferrous metals, particularly aluminum, nickel, and their alloys, are used for smooth finish and bright silvery color. Copper and its alloys form a whole set of red, gold, and yellow metals.

Besides these seven criteria used for comparison of the nonferrous metals, there are other characteristics which may be of even greater importance in particular cases. They include cost, mechan-

ical properties, influence of expected impurities on properties, forms available, and methods to be used in fabrication. In the following sections the general characteristics of nonferrous metals of commercial importance will be discussed briefly.

Aluminum and Its Alloys

8.2 COMMERCIAL ALUMINUM

Although aluminum is a relatively new metal in industry, it has rapidly come into wide use, particularly because of its adaptability to the expanding airplane industry. Increasing production and less expensive electrical power has brought about progressive reduction in cost until now its price per lb is lower than that of copper.

The principal ore of aluminum is bauxite, $Al_2O_3 \cdot H_2O$. After the ore is mined, it is crushed and usually concentrated by the Boyer process. The bauxite is first digested by caustic soda forming sodium aluminate which is separated by filtration. This is converted to aluminum hydrate by precipitation, and then converted to the oxide by calcination. This alumina, Al_2O_3, is reduced (deoxidized) by electrolysis of a molten solution at 1000 C.

Because the electrolyte is an impure mineral, the aluminum produced in electrolysis usually contains substantial quantities of other metals. The nominal purity of structural aluminum is 99.2 per cent, whereas that of aluminum conductor is 99.5 per cent. The principal impurities in commercial aluminum are iron, silicon, and copper (zinc is also present in scrap aluminum). Quantities of each can be approximately controlled by the producers. They do not always have an undesirable effect on the properties, however, and in many applications their effect is good. For instance, chemically pure aluminum is very soft and weak; commercial aluminum has about twice the strength of the pure grade. The thermal and electrical conductivities of commercial aluminum are, on the other hand, only slightly below the conductivities of chemically pure aluminum.

Aluminum and its alloys are used principally in applications which demand one or more of its outstanding characteristics: (a) good strength, (b) light weight, (c) high thermal and electrical conductivity, and (d) good corrosion resistance. These are discussed below.

8.3 WEIGHT AND STRENGTH

Aluminum and aluminum-base alloys have densities of about 0.10 lb per cu in., compared with 0.32 for copper, 0.28 for steel, and 0.065 for magnesium. By volume, aluminum is less than half as expensive as copper; it is the cheapest material for nonmagnetic parts of a given volume.

Commercial aluminum in the annealed or cast condition has a tensile strength about one-fifth that of structural steel. The strength may be more than doubled by cold working; and by alloying aluminum with various other metals the strength may be even further increased. The ratios of strength to weight for some of the hardened aluminum alloys are as high as for any other structural material. Although some steels have comparable strength-to-weight ratios, the structural aluminum alloys have proved themselves superior in many applications, particularly in lightweight transportation equipment. Their superiority can be explained as follows.

Structural members are often column loaded and fail by buckling. The load sufficient to cause failure of the entire column depends upon the moment of inertia of the column cross-section. In order to increase the load capacity for a given amount of material, special shapes, such as I-beams or tubes, are used. The effective increase is limited by the thinnest part of the column. A material like aluminum alloy, which has thick sections in proportion to its weight, is ideal for lightweight columns. A typical application is in a stressed airplane skin, where compressive stresses between points on the skin may cause it to wrinkle. An aluminum alloy skin $\frac{1}{16}$ in. thick would stand a great deal more column loading than a steel sheet 0.02 in. thick, even though they are of the same weight and their strengths in direct tension or compression would be about equal. This comparison holds true for the structural members within the airplane; and for small, light planes, wood may even be preferred to aluminum.

8.4 CONDUCTIVITY

The thermal and electrical conductivities of commercially pure aluminum are about 60 per cent of those of copper. This is high enough to bring about its use as the conductor for many electric power lines. In order to have the same resistance as a copper conductor, the aluminum wire should have a 65 per cent larger cross-sectional area. Its weight would still be only half that of an

equivalent copper wire, and if the cost of aluminum and copper per pound were the same, the aluminum conductor would cost only half as much as the copper one. This economy cannot be fully realized because the aluminum is weaker and must be reinforced by a steel core in order to support its own weight and service loading.

Bare aluminum conductor has, during normal years, consumed about one-sixth of the United States aluminum production. Insulated aluminum cable has not been used because the large wire cross section makes it necessary to use about 30 per cent more insulating material than for a copper wire having the same resistance, thus raising the over-all cost of insulated aluminum conductor above that of insulated copper.

8.5 FABRICATION

The melting point of pure aluminum is 1215 F, and the alloys usually melt at lower temperatures. These low melting points make them unsuitable for high temperature applications, but do facilitate casting in sand, permanent molds, or under pressure in dies. The physical properties of aluminum alloys cast in metal molds are, in general, better than those of the same alloys cast in sand. The metal mold chills the molten metal far more rapidly, and the grains are given only a short time to grow. In a casting which has a varying cross section, the thinnest sections will cool first and have the finest grains.

Pure aluminum is seldom used for castings because of its hot shortness and high shrinkage. It is used only where high conductivity is demanded, for example, in cast squirrel-cage induction-motor rotors.

First forming is usually done at a plastic temperature of 750 to 900 F, because aluminum and aluminum alloys are relatively brittle in ingot form. The hot forming may be continued at 500 to 900 F, depending upon the type of alloy and the process. Many forms, such as the larger sizes of tubing, rod, or plate, are extruded or hot rolled to their final forms. The smaller tubing and other forms such as wire and sheet are finished by cold working.

A relatively new development in aluminum products is the use of pressings, which are made from suitably shaped slugs of alloys and squeezed into shape in a press. Pressings may be made hot or cold, using any alloy that can be extruded or forged.

Aluminum is inherently very reactive and it spontaneously forms a thin oxide film when exposed to the air. This oxide film must be removed and prevented from reforming while soldering; otherwise a very weak joint will result. Even with proper precautions, the soldering of aluminum is usually unsatisfactory, because the joint between aluminum and any solder thus far developed will, in time, decompose electrolytically. Brazing with alloys having melting points near that of 2S and 3S, aluminum is satisfactory, but control is difficult and brazing fluxes *must be removed*.

The oxygen coating offers some difficulty to welding. In non-pressure welding, the oxide must be removed by fluxes, and for resistance welding it may be necessary to brush off the oxide coat or remove it by etching. If these precautions are taken, however, good welds can be made by any of the usual welding methods.

Aluminum has a coefficient of thermal expansion 50 per cent greater than copper and twice that of steel and cast iron. Where large temperature changes are encountered in an assembly of aluminum parts with those of other metals, allowance must be made for this difference in expansion.

The machining of aluminum varies widely from poor for annealed pure metal to good for hardened or cold-worked alloys. Although special tools and techniques have been developed, the tools used for other harder metals can be used with satisfactory results if production quantities are small.

8.6 CORROSION RESISTANCE

The thin oxide coating that forms on aluminum and its alloys serves as protection against corrosion. Erosion or abrasion will, of course, remove this oxide and will accelerate corrosion. Constant rubbing of parts may make this particularly severe.

Commercially pure aluminum (2S) * is often used for such shapes as sheet, tubing, and rod where good general corrosion resistance is required. An alloy with approximately equal corrosion resistance and considerably higher strength contains 1 to 1.5 per cent manganese, the remainder aluminum (3S). Alloys of aluminum with silicon and magnesium also have good resistance to corrosion, but zinc and iron alloys appear to have less corrosion resistance.

The alloys of aluminum with copper, tin, or zinc are attacked to various degrees by local electrolytic corrosion. The local cells may

* Designation used by the Aluminum Co. of America.

be broken up, however, by periodic cleaning of dirt and moisture from the surface. Oil or wax is good for temporary protection.

Oxide Coatings. A heavy surface oxide may be artificially produced by either of two methods. One method, which produces a film with considerably greater protective power than the natural oxide coating involves boiling the metal in a chromate or carbonate solution.* A second method, called *anodizing,* is more expensive, but causes formation of an even better protective coating. In this method the article is made the anode in an electrolyte such as sulfuric acid, chromic acid, or oxalic acid. The color of the anodic coating may be controlled by surface condition and composition of the alloy, by the type of electrolyte, or by dyeing the anodic coat. Both the chemically and anodically produced oxide films are improved by "sealing" with dichromate solutions followed by a hot-water rinse. In severely corrosive atmospheres anodic coatings must be kept clean in order to prevent breakdown of the coating and pitting of the aluminum beneath.

Painting. A suitable primer or treatment must be used before painting to make the surface chemically inert. An anodic coating is an ideal paint base, although often an anodic coating is painted only for appearance, not to improve its corrosion resistance. The surface can be prepared more cheaply by one of several chemical-immersion treatments, but none of these gives corrosion protection equal to anodizing. For best corrosion resistance, the surface of the paint should be impermeable to moisture, and for this purpose aluminum paint with a synthetic resin is excellent.

Metallic Coatings. Nearly all the alloys have poorer corrosion resistance than commercial aluminum, and when corrosion protection is needed, some alloys are coated with commercially pure aluminum. The coating oxidizes and gives high electrolytic corrosion resistance, but in addition its electrolytic properties (see Chapter 5) are such that it prevents the corrosion of the base metal at the sheared edges or where the coating is deeply scratched. The entire coating will be corroded away before the base metal in the vicinity will be disturbed. The usual thickness of the coat is about 5 per cent of the total thickness of the part, and it is applied during the hot rolling of the shape. Common trade names are Alclad and Pureclad.

Rolled shapes, castings, and assemblies which cannot be readily

* Trade names are Alrok and Pylumin.

clad may be protected by a sprayed coating of aluminum, zinc, or cadmium. These deposits are porous, and their protective action is caused only by their electrolytic properties.

Aluminum can be plated with zinc, cadmium, nickel, and chromium, all of which offer mechanical protection. Zinc and cadmium also provide electrolytic protection against corrosion, but nickel and chromium platings provide their respective corrosion resistances only if their coating is continuous. The difference in elastic modulus between aluminum and the platings limits the distortion which may be placed on the plated products.

8.7 ALLOYS

The aluminum alloys are stronger than pure aluminum. Some of them can be hardened by precipitation heat treatment, and all can be hardened by cold working (see Table 8.1).

Nonprecipitation Hardening Alloys. The aluminum-casting alloys generally contain higher percentages of alloying elements than the alloys used in wrought forms. The higher percentages of added elements facilitate casting but make working more difficult.

A 5 per cent silicon alloy has been used considerably for sand and permanent-mold castings because it has good resistance to corrosion and excellent casting qualities (high fluidity and freedom from hot shortness). It is generally suitable for pressure-tight castings and can be made in thin sections.

The 13 per cent silicon alloy is used principally for die casting. It has the good casting properties and corrosion resistance characteristic of silicon alloys.

Of the wrought aluminum alloys that cannot be precipitation hardened, the 1.25 per cent manganese alloy is one of the more important. It is stronger and harder than pure aluminum, and, unlike other alloys, its corrosion resistance is about as good as that of pure aluminum. It is used for conduit and pipe, and for cooking utensils, since it retains its work hardness very well after exposure to elevated temperatures.

An alloy which has considerably higher tensile and yield strengths than the aluminum-manganese alloy contains 2.5 per cent magnesium and 0.25 per cent chromium, besides aluminum. It has good corrosion resistance, especially to salt water, good workability, and high fatigue resistance.

Precipitation-Hardening Alloys. Some of the aluminum alloys, when water quenched from high temperatures and then aged, either

Table 8.1 Typical Properties of Representative Aluminum Alloys

Designation*	Tensile Strength, M psi	Yield Strength, M psi 0.2% offset	Elongation, %,† in 2 in.	Shear Strength, M psi	Endurance Limit, M psi, rev. bend 500 × 10⁶ cycles	Hardness, BHN 500 g/10 mm	Electric Resistivity, microhm-cm at 68 F	Thermal Conductivity, cal/cm²/cm/s/°C at 77 F	Solidus, °F	Precipitation Temp, °F	Uses ‡	Nominal Composition, %
Wrought—not hardenable by H.T.												
AP—Annealed	6.9	1.8	49 (⅛S)			17	2.655	0.53	1220.4		High Purity. Used for cladding	99.996 Al
2S—Annealed	13	5	45 (½R)	9.5	5	23	2.922	0.52	1190	⋮	Forms 1, 2, 3, 4. Easily formed, good corrosion resistance, low strength	99.0 min Al
H18—cold worked—full hard	24	21	15 (½R)	13	8.5	44	3.025		1190			
3S—Annealed	16	6	30 (⅛S)	11	7	28	3.448	0.46	1190		Forms 1, 2, 3, 4. Stronger than 2S, good workability, weldability, and corrosion resistance	1/1.5 Mn, bal. Al
H18—cold worked—full hard	29	25	4 (⅛S)	16	10	55	4.310	0.37	1190			
52S—Annealed	29	14	25 (⅜R)	18	17	45	4.926	0.33	1100		Forms 1, 2, 3. Good workability, fatigue strength, and corrosion resistance	2.2/2.8 Mg, 0.15/0.35 Cr, bal. Al
H38—cold worked—full hard	41	36	7 (⅜R)	24	19	85	4.926	0.33	1100			
56S—Annealed	42	20	35 (½R)		20		5.045	0.28	1055		Form 2 Wire products where corrosion resistance is needed	4.5/5.6 Mg, 0.05/0.2 Cr, 0.05/0.20 Mn, bal. Al
H38—full hard	58	48	7 (½R)		22		6.386	0.26	1055			
Wrought—hardenable by H.T.												
11S—T3 sol. tr. and cold worked	53	47	15 (⅜R)	30	12.5	95	4.31	0.37	995		Form 2. Machinability and strength for screw machine parts and machined forgings	3.5/6 Cu, 0.2/0.7 Pb, 0.1/0.7 Bi, bal. Al
T8 precip., C.W., and aged	57	44	14 (½R)	33		100	⋮		995	330–340		
14S—Annealed	27	14	18 (1R)	18	11	45	3.448	0.46	950		Forms 1, 6, and Extrusions. Good formability. Used for heavy-duty forgings	3.9/5 Cu, 0.5/1.2 Si, 0.4/1.2 Mn, 0.2/0.75 Mg, bal. Al
T6 precip. hardened	70	60	13 (1R)	42	18	135	4.31	0.37	950	335–345		
17S—Annealed	26	10	22 (⅜R)	18	11	45	3.831	0.41	955		Forms 1, 2, 3, 4, 5, 6. Relatively high strength and good formability. Used for fittings, hdwe., and screw machine parts	3.5/4.5 Cu, 0.4/1.0 Mn, 0.2/0.8 Mg, bal. Al
T4 precip. hardened	62	40	22 (½R)	38	18	105	5.747	0.29	955	Room T.		

Alloy and temper											Temp.	Characteristics	Composition
29S—Annealed	27	11	22	(½R)	18	12	42	3.448	0.45	935	Room T.	Forms 1, 2, 3, 4, 5. Stronger than 17S. Same uses	3.8/4.9 Cu, 0.3/0.9 Mn, 1.2/1.8 Mg, bal. Al
T4 precip. hardened	68	46	22	(½R)	41	18	120	5.747	0.29	935	335–345	Form 6. Fairly high strength forging alloy	3.9/5 Cu, 0.4/1.2 Mn, 0.50/1.2 Si, bal. Al
29S—T6 precip. hardened	57	35	18	(½R)	35	18	110	4.31	0.37	970	335–345		
32S—T6 precip. hardened	56	46	8	(½R)	38	16	125	4.926	0.33	990	335–345	Form 6 Low expansion and good forgeability for uses like forged pistons	11.5/13.5 Si, 0.5/1.3 Cu, 0.5/1.3 Ni, 0.8/1.3 Mg, bal. Al
53S—Annealed	16	7	35	(½R)	11	8	26	3.831	0.41	1075	..	Forms 1, 2, 3, 4. Good workability and corrosion resistance. Used for petroleum-process parts, beer barrels, and naval and architectural construction	1.1/1.4 Mg, 0.45/0.65 Si, 0.15/0.35 Cr, bal. Al
T4 precip. hardened	33	20	30	(½R)	20	13	65	4.31	0.37	1075	345–355		
T6 precip. hardened	39	33	20	(½R)	24	13	90	4.31	0.37	1075	315–325		
61S—Annealed	18	8	22	(⅛B)	12.5	9	30	3.83	0.41	1080	..	Forms 1, 2, 3, 4. Good strength, workability, and corrosion resistance	0.8/1.2 Mg, 0.4/0.8 Si, 0.15/0.4 Cu, 0.35 Cr, bal. Al
T4 precip. hardened	35	21	22	(⅛B)	24	13.5	65	4.31	0.37	1080	345–355		
T6 precip. hardened	45	40	12	(⅛B)	30	13.5	95	4.31	0.37	1080	315–325		
76S—T6 precip. hardened	88	80	10	(½R)	47	22.5	150	5.747	0.29	890	245–255	Form 1 and Extrusion. Very high strength with good corrosion resistance	2.1/2.9 Mg, 5.1/6.1 Zn, 1.2/2 Cu, 0.1/0.3 Mn, 0.15/0.4 Cr, bal. Al
Cast—not hardenable by H.T.													
12—Die cast	37	18	1.8	(½R)	.	15	.	4.431	0.37	1065	..	Excellent castability for thin-walled and intricate die castings	11/13 Si, bal. Al
43—Sand cast	19	9	6	(½R)	14	6.5	40	4.66	0.35	1070	..	Die castings with above-average ductility and corrosion resistance. Sand and perm.-mold castings of good castability, moderate strength, and corrosion resistance	4.5/6 Si, bal. Al
Perm.-mold cast	24	9	9	(½R)	18	.	45	4.66	0.35	1070	..		
Die cast	30	16	9	(½R)	18	17	45	4.66	0.35	1070	..		
85—Die cast	40	24	5	(½R)	.	22	.	6.158	0.27	970	..	General-purpose die-casting alloy with high impurities	4.5/5.5 Si, 3 5/4.5 Cu, bal. Al
A-108—Perm.-mold cast	28	16	2	(½R)	25	.	70	4.66	0.34	960	..	General-purpose perm.-mold casting alloy with good castability, weldability, and soundness	5/6 Si, 4/5 Cu, bal. Al
112—Sand cast	24	15	1.5	(½R)	20	9	70	5.747	0.28	975	..	Used for sand castings which must be dense and pressure tight	6/8 Cu, 1/3 Si, 2 Zn max, bal. Al
A-132—Perm.-mold cast (T551)	36	28	0.5	(½R)	24	.	105	5.945	0.28	1000	..	Low expansion, high-temp strength, wear resistance for automobile pistons, pulleys, etc.	11/13 Si, 0.7/1.3 Mg, 2/3 Ni, 0.5/1.5 Cu, bal. Al
214—Sand cast	25	12	9	(½R)	20	5.5	50	4.926	0.33	1075	..	Excellent resistance to corrosion and tarnishing. A214 with 1.4 to 2.2 Zn is for perm.-mold castings and has slightly higher mech. properties	3.2/4.3 Mg, bal. Al
380—Die cast	46	25	3	(½R)	.	19	.	6.386	.	970	..	General-purpose alloy of greater castability than "85"	7.5/9.5 Si, 3/4 Cu, bal. Al

335

Table 8.1 Typical Properties of Representative Aluminum Alloys (Continued)

Designation * §	Tensile Strength, M psi	Yield Strength, M psi 0.2% offset	Elongation, %† in 2 in.	Shear Strength, M psi	Endurance Limit, M psi, rev. bend 500 × 10⁶ cycles	Hardness, BHN 500 g/10 mm	Electric Resistivity, microhm-cm at 68 F	Thermal Conductivity, cal/cm²/cm/c/sec at 77 F	Solidus, °F	Precipitation Temp., °F	Uses ‡	Nominal Composition, %
Cast—hardenable by H.T.¶												
40E ‖—Sand cast, aged	35	25	5 (½R)	26	9	75	4.926	0.33	1060	365 F or aged R.T. 21 days	Shock resistance, dimensional stability, machinability, and low distortion by heat treatment	5/6 Zn, 0.5/0.65 Mg, 0.4/6 Cr, 0.1/0.3 Ti, bal. Al
122—Sand cast, T61	40	30	<0.5 (½R)	29	8.5	115	5.225	0.31	1005	305–315	Good high-temperature strength, hardness, wear resistance, and machinability for aviation pistons and cylinder heads	92./10.8 Cu, 0.15/0.35 Mg, bal. Al
Perm.-mold cast, T561	37	35	<0.5 (½R)	27	8.5	115			1005	335–345		
195—Sand cast, T4	32	16	8.5 (½R)	24	6	60	4.926	0.33	1020	Sol. treated 950 F	High-tensile properties and good machinability for wheels, housings, and fittings. B195 with 2.5 Si perm.-mold casting alloy and has slightly higher properties	4.5/ Cu, 1.2 Si max, bal. Al
Sand cast, T6	36	24	5 (½R)	30	6.5	75	4 66	0.35		305–315 3.5 hr		
319—Sand cast, T6	36	24	2 (½R)	.	10	80	6.386	0.26	950	305–315	Good casting, welding, and strength properties with pressure tightness	2.5/4.5 Cu, 5/7 Si, bal. Al
Perm.-mold cast, T6	40	27	3 (½R)			95	6.158	0.26	950	305–315		
355—Sand cast, T6	35	25	2.5 (½R)	30	8.5	80	4 789	0.34	1075	305–315	Good castability, weldability, and pressure tightness	4.5/5.5 Si, 1/1.5 Si, 0.4/0.6 Mg, bal. Al
Perm.-mold cast, T6	43	27	4 (½R)	30	9	90	4.421	0.36	1075	305–315		

* Designations are those of Aluminum Co. of America.

† Parentheses include size in inches and R for rounds or S for sheet specimens.

‡ Code for available forms:
1. Sheet and plate.
2. Bar, rod, shapes, wire.
3. Tubing.
4. Rivets.
5. Bolts, nuts, studs.
6. Forgings.

§ Other properties for aluminum alloys are approximately as follows:
Mod. of elasticity, E, 10,300,000 psi.
Shear mod., G, 3,850,000 psi.
Poisson's ratio, σ, 0.33.
Density, 0.096 to 0.105 lb/cu in.
Specific heat, 0.23/C cal/gm.
Coeff. of thermal exp., 20 to 23 $\times 10^{-6}$/°C at −20 to 100 C.
Annealing temp., 650–750 F—wrought, not hardenable.

Annealing temp., 750–800 F—wrought hardenable.
Recrystallization temp., 650 F with 50% C.W.
Hot-working temp. 500–900 F.
Solution treatment, 920–980 F for wrought-hardenable alloys.

‖ Frontier Bronze Corp. designation.

¶ Heat treatments are also applied to these alloys for plaster mold, precision investment, and centrifugal castings. Die castings are seldom heat treated because of blistering.

naturally at room temperature or artificially at a slightly elevated temperature, show remarkable increases in strength and hardness. They are called the *strong alloys* of aluminum.

Several copper alloys are used for general sand and permanent-mold casting but an 8 per cent copper alloy has been most popular. Iron and silicon should be accurately controlled at about 1 per cent each for best casting and physical characteristics. The cost of the finished product is often lower when made of the 8 per cent copper alloy than if made of other alloys, and this has been one reason for its wide use for cast automobile engine crankcases, oil pans, and transmission cases. Its principal disadvantage is relatively poor corrosion resistance.

Alloys containing 4 per cent copper and small but accurately controlled percentages of iron and silicon have fairly good resistance to damage by corrosion, although their surface may be blackened. They are somewhat harder to cast than the 8 per cent copper alloys, but the difficulty has not prevented their wide use. The castings may be solution heat treated and quenched, after which they are in the condition of maximum ductility and impact resistance. If high yield strength rather than impact resistance is desired, the casting is hardened by furnace heating, which causes precipitation.

There are two groups of precipitation hardening aluminum-silicon alloys, both of which have better casting characteristics and corrosion resistance than the aluminum-copper alloy. The 5 per cent silicon, 1.25 per cent copper, 0.5 per cent magnesium alloy was developed for liquid-cooled cylinder heads, and consequently is used wherever strong, pressure-tight castings are needed. A 7 per cent silicon, 0.3 per cent magnesium alloy is also used for complicated and pressure-tight castings, and, like the 5 per cent silicon alloy, it is particularly adapted to permanent-mold casting.

Alloys of aluminum with about 10 per cent magnesium may be precipitation hardened to obtain a tensile strength as high as that of any common aluminum-base casting alloy. They also have good impact strength and corrosion resistance, but because of the high magnesium content, special foundry techniques must be used to avoid surface oxidation of the casting.

A common precipitation-hardening wrought alloy is Duralumin, or 17S, which hardens spontaneously in about 4 days at room temperature. The hardening begins so rapidly that forming should be done during the first few hours after quenching. If the forming

is delayed, the aging of the alloy should be suspended by keeping the parts in liquid air or some other freezing medium.

The inconvenience of handling the alloys which age spontaneously has led to development of new alloys whose compositions are variations upon that of Duralumin. They will not age harden at room temperature, but are hardened by furnace heating to 300 or 350 F for 8 to 24 hr.

Alloys such as 53S, 61S, and 75S are adapted to drawing and forming when in the soft state. When forming is complete, the part can be precipitation hardened by aging in a furnace with little distortion. Unlike most of the other strong alloys of aluminum, 53S has excellent resistance to weathering and corrosion. Variations in its composition produce alloys which have better mechanical properties for certain applications, but which have less corrosion resistance.

Copper and Its Alloys

8.8 PRODUCTION OF COPPER

Some Egyptian statuettes dating from 2600 B.C. are made of practically pure copper. It is probable that the metal was mined as uncombined native copper in Nubia or Ethiopia. In the United States similar deposits have been mined in Vermont and Michigan, but today the low copper content of the remaining deposits makes them marginally competitive with sulfide and oxide ores. The sulfide and oxide ores are widely distributed throughout the world. The sulfide types (1–2 per cent Cu) have been mined particularly in the southwest and Rocky mountain regions. The red oxide, Cu_2O, has come principally from South America.

Over 1 million tons of copper are refined per year in the United States. The processes used are indicated in Fig. 8.1. Electrolytic tough-pitch copper comprises a large part of domestic consumption and its refinement is described below.

Electrolytic Copper. This metal is commonly extracted in the United States from low-grade sufide ores (1–2 per cent Cu). The concentrated ore is roasted to reduce the sulfur content and then the roasted ore is smelted in the reverberatory furnace to a mixture of copper and iron sulfides called *matte*. The molten matte is charged into a converter (similar to the Bessemer, Fig. 7.1), where streams of air oxidize and blow out the sulfur, first from the iron sulfide, permitting the iron present to go into slag.

The product, *blister copper*, is further refined in a reverberatory furnace, and then cast into *anode bars* for electrolytic refining. During this operation spongy copper forms on the cathode. This
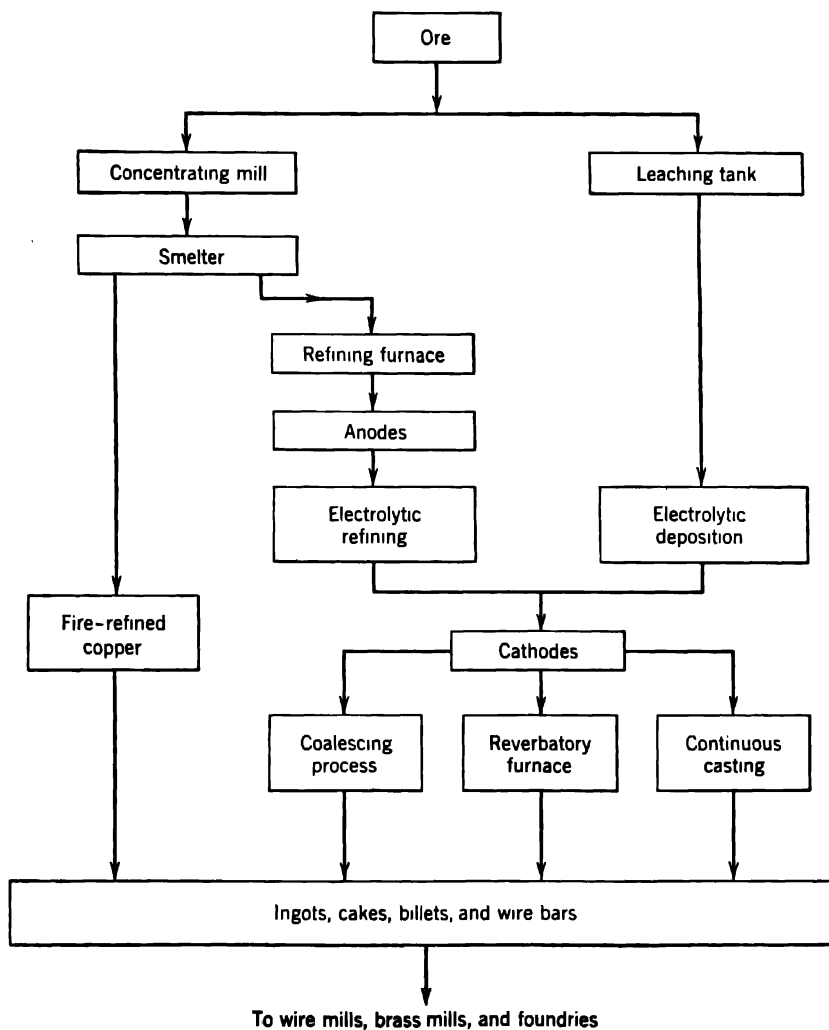
Fig. 8.1. Processes for refining copper ores.

is later melted, treated to reduce oxides, and cast into molds. The most commonly used reducing method is the stirring of the melt with a green log, an operation called "poling." The product, as cast, will contain up to 0.07 per cent oxygen, and is known as

electrolytic tough-pitch copper. Its properties would be much improved for some applications if its oxygen content were lower.

Oxygen-Free and Deoxidized Copper. The source of most of the oxygen in electrolytic tough-pitch copper is the hot oxidizing furnace atmosphere. If the melt is protected by a furnace atmosphere of chemically inert gas, and if the casting is done under similarly protected conditions, a high-grade, oxygen-free copper can be produced.

Low-oxygen-content copper may also be produced by deoxidation with a strong reducing agent such as phosphorus or silicon, but this copper has 10 to 15 per cent lower conductivity than electrolytic tough-pitch copper. A high conductivity grade of deoxidized copper can be made by carefully controlling the use of phosphorus, or by employing calcium, lithium, or boron, which leave no metallic residue in the copper.

Lake Copper. Deposits of native nearly pure copper are mined in northern Michigan. This *lake copper* is of such high purity that all refining is done in the blast furnace, and the refined metal contains about 10 oz of silver per ton (0.03 per cent) and sometimes up to 0.3 per cent arsenic. If no arsenic is present, it has a conductivity equal to that of electrolytic copper. If arsenic is present in appreciable quantity, it is known to the trade as "arsenical lake copper," and its conductivity is not as good as that of the electrolytic grade. It does have better resistance to scaling and corrosion at high temperature, however, and has been used principally for condenser tubing and firebox parts.

Although the lake region was the principal United States source of copper before 1900, economical methods of working low-grade sulfide ores have greatly reduced its importance. When the demand for arsenical or silver-bearing copper is greater than the supply, the deficiency may be made up by adding arsenic or silver to electrolytic copper.

8.9 CONDUCTIVITY OF COPPER

The high electrical conductivity of copper (second only to silver) has led to use of large quantities in electrical wire and electrical machines. Conductivity is important in such applications but, unfortunately, the usual alloying agents and impurities, except for silver, reduce it. The International Standard resistance for annealed copper is 0.15328 ohm per mg at 20 C (10.371 ohms per cir mil ft). The conductivity of a copper sample is often expressed as a percentage of the conductivity of this standard sample. Since

the establishment of this standard, refining methods have been improved so much that copper of higher conductivity than the standard is now fairly common. Some samples run as high as 102 per cent conductivity, and a minimum standard of 99.3 per cent is frequently used. Electrolytic ingots usually have above 97.6 per cent conductivity.

8.10 RECRYSTALLIZATION OF COPPER

Copper is usually cold worked to its final size or shape, e.g., wire is drawn through dies, and bar and sheet are rolled. This working, through the mechanism of work hardening, increases the strength and hardness but decreases the ductility.

If copper that has been cold worked is heated above the recrystallization temperature (400 to 500 F), it will return to its original soft, weak, and ductile condition (see Fig. 8.2). The more it has been cold worked, the lower the temperature at which it will soften.

Copper alloys of high recrystallization temperatures are used to avoid a loss in strength by recrystallization of cold-worked parts exposed to somewhat elevated temperatures. Several alloying agents may be used, but silver has the greatest effect. A few ounces of silver per ton raises the recrystallization temperature as much as 200 F. If cold-worked copper wires or parts are to be soldered and must retain their cold-work strength after soldering, they should be made of silver-bearing copper or of lake copper.
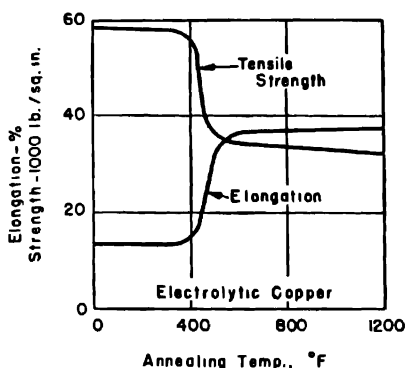
Fig. 8.2. Effect of annealing upon the tensile strength and elongation of copper. (*Bassett and Davis, data from Metals Handbook, 1939 edition, American Soc. Metals.*)

8.11 INTERCRYSTALLINE FAILURE OF COPPER

If copper is moderately stressed at high temperatures and during a long enough period of time, it will fail by creep. Table 8.2 shows results of tests on samples stressed at 16,000 lb per sq in., which was about half their ultimate strength at room temperature. The data show that the temperature necessary to produce a brittle in-

Table 8.2   Intercrystalline Failure of Copper

(Stress, 16,000 lb/sq in.)

Time to Fail, in Hours

Temp., °F	Electrolytic Copper	14 oz/ton Silver-Bearing Copper
482	1.5	46
455	2	157
392	19	1048
337	110	No failure

tergranular fracture under stress and after a given time is at least 100 F higher for silver-bearing copper than for electrolytic copper.

8.12   HYDROGEN EMBRITTLEMENT OF COPPER

The oxygen remaining in electrolytic tough-pitch copper is in the form of cuprous oxide (Cu_2O). When this grade of copper is exposed to a reducing gas at temperatures above 750 F, the hydrogen in the gas diffuses into the copper and reacts with the cuprous oxide to form metallic copper and water vapor. The reaction is

$$H_2 + Cu_2O \rightleftharpoons 2Cu + H_2O$$
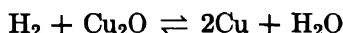
Hydrogen diffuses into copper faster than the water vapor formed can escape by diffusion and an internal pressure sufficient to rupture the metal is built up. Cracks and holes appear at the grain boundary (see Fig. 8.3) and make the copper brittle.

Wherever copper parts are to be exposed to reducing gases at temperatures above 750 F, they should be made of deoxidized copper.

8.13   FABRICATION

Tests have shown conclusively that thoroughly deoxidized copper should always be specified for copper parts that are to be gas welded. This type of welding should not be used for tough-pitch copper because the copper would become spongy and porous at the weld. Spot or seam welding of high-conductivity copper is not done commercially unless the surfaces have been tin plated. Neither deoxidized nor electrolytic grades can be cut by an oxidizing gas flame because of their high thermal conductivities. They are, however, easily butt welded, silver brazed, and soldered.

Copper castings are made almost entirely in sand molds. The technique of casting high-conductivity copper is especially difficult since considerable skill is required in handling the reducing agents. The molten metal is viscous and will not fill a mold of great intricacy. Copper is hot short and the hot casting will break as it cools if the mold or the design prevents shrinkage. If very high
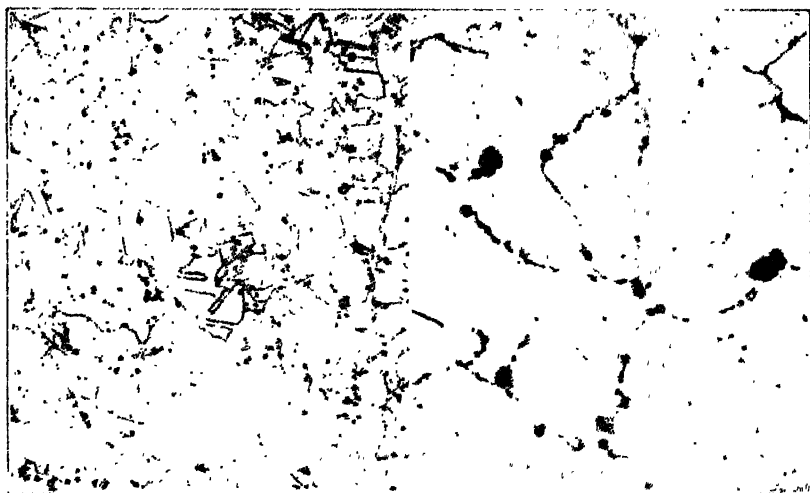
Fig. 8.3. *Left,* photomicrograph of annealed tough-pitch copper, ×250. *Right,* photomicrograph of sample on left after two hours at 800 C in hydrogen, ×250. Note voids along the grain boundaries.

conductivity is not required, one of many casting alloys may be used. They are stronger and more easily machined and handled in the foundry, and as a result the finished casting will be less costly than if made of high-conductivity copper.

8.14 COPPER-ZINC ALLOYS

The most widely used copper alloys are *brasses*. They are fundamentally a binary alloy of copper with as much as 50 per cent zinc, but often their properties are modified by addition of other elements in small amounts. The brasses are stronger than copper and are used in structural applications, but the increase in strength sacrifices both electrical and thermal conductivity.

Brasses containing more than 64 per cent copper are structurally a single-phase solid solution of zinc and copper, termed the "alpha"

Table 8.3 Typical Properties of Representative Wrought Copper Alloys

Commercial Designation	Tensile Strength, M psi		Yield Strength, ½% Offset, M psi		Elongation, % in 2 in.		Shear Strength, M psi		End Limit, M psi, 20×10⁶ cycles		Mod. of Elast. E ×10⁶ psi	Hardness, Rockwell		M.P. or Solidus, °F	Density, lb/cu in.	Volume Electrical Conduct. % of IACS	Uses	Nominal Composition, %
	Hard	Soft	Hard	Soft	Hard	Soft	Hard	Soft	Hard	Soft		Hard	Soft					
Not hardenable by heat treatment																		
Pure copper																		
Electrolytic T.P. copper	:50	32 33	:45	10	6–12	45 50	28	22	13	11	16	F90	F40	1981.4	0.324 0.3217	103.6 101	Sheet (also rod and wire) for electrical parts	99.9+ Cu and Ag min
Deoxidized copper	55	32	50	10	8	45	28	22	19	11	17	F95	F40	1981	0.323	85	Sheet (also rod, wire, tube, and pipe) for hot- and cold-worked parts, suited to welding	99.9 Cu and low P
Gilding brass (95% Cu)	56	34	50	10	5	45	37	28	:	:	17	B64	F46	1920	0.320	56	Sheet (also wire) for jewelry trade—hot and cold forming	94/96 Cu, bal. Zn
Commercial bronze (90% Cu)	61	37	47	12	5	45	38	28	21	·	17	B70	F53	1870	0.318	44	Sheet (also wire) for screening, radiators, bullets	89/91 Cu, bal. Zn
Red brass (85%)	70	40	57	12	5–8	47–55	42	31		20	17	B77	F59	1810	0.316	37	Sheet (also wire, tube, and pipe) of good corrosion resistance	84/86 Cu, bal. Zn
Low brass (80%)	74	44	59	14	7	50	43	32	23		16	B82	F61	1770	0.313	32	Sheet (also wire) of excellent hot-working properties	78.5/81.5 Cu, bal. Zn
Cartridge brass (70%)	77	47	64	15	8	62	44	33	21	13	16	B82	F64	1680	0.308	28	Sheet (also rod, wire, and tube) for cold deep drawing	68.5/71.5 Cu, bal. Zn
Yellow brass	74	49	60	17	8	57	43	34	14	12	15	B80	F68	1660	0.306	27	Sheet (also rod and wire) good for cold-work parts	64/67.5 Cu, bal. Zn
High-leaded brass	74	49	60	17	7	52	43	34	:		15	B80	F68	1630	0.306	26	Sheet, particularly machined clock parts	62.25 Cu, 35.75 Zn, 2 Pb nominal
Muntz metal (annealed and ½ hard)	70	54	50	21	10	45	44	40			15	B75	F80	1650	0.303	28	Sheet (also rod) good hot-working properties, forgings, trim, bolts, etc.	59/63 Cu, bal. Zn
Naval brass (0.250 annealed sheet and ½ hd. rod)	80	60	57	28	20	45	45	41	15		15	B85	B58	1630	0.304	26	Sheet (rod and tube) for hot and cold forming, and salt exposure	59/62 Cu, 0.5/1 Sn
Phosphor bronze (1.25%) (E)	65	40	50	14	8	48	:	·	:		17	B75	F60	1900	0.321	43	Sheet (also wire) suited to many cold-forming operations	98.5 Cu min, 1/1.5 Sn
Phosphor bronze (5%) (A)	81	47	75	19	10	64	.	37	.		15	B87	B26	1750	0.320	18	Sheet (also wire and rod) good for cold forming, but is hot short	3.5/5 8 Sn, 0.03/0.35 P, bal. Cu

244

Material																Typical uses	Composition
Phosphor bronze (8%) (B)	93	80	72	24	10	65			22		16	B93	F75	1620	0.318	13	Sheet (also wire and rod) same as 5% but stronger	7/9 Sn, 0.03/0.35 P, bal. Cu
Nickel silver (A)	88	58	74	25	3	40					18	B87	B40	1960	0.316	6	Sheet (also rod and wire) suited to cold forming. Good tarnish and corrosion resistance for tableware, instruments	63/66.5 Cu, 17/19.5 Ni, bal. Zn
Nickel silver (B)	100	60	85	27	3	40					18	B91	B55	1930	0.314	5.5	Sheet (also rod and wire) less cold forming but stronger than A	53.5/56.5 Cu, 16.5/19.5 Ni, bal. Zn
Low-silicon bronze (A)	94	60	58	25	8	60	57	43	23	16	15	B93	B62	1780	0.308	7	Sheet (also rod, wire, and tube) suited to hot and cold forming with good mech. prop. and corrosion resistance	94.8 min Cu, 2.75/3.5 Si, 1.5 Mn or Zn max
High-silicon bronze (B)	70	40	55	15	15	50	40	28			15	B80	F55	1890	0.316	12	Rod (also sheet, wire, and tube) similar to A. Used for hardware, etc.	96 min Cu, 0.75/2.00 Si, 0.75 Mn max
Manganese bronze (annealed and ½ hard)	84	65	60	30	19	33	48	42			15	B90	B65	1590	0.308	24	Rod, forgings upsettings, hot-headed and punched parts	57/60 Cu, 0.80/0.20 Fe, 0.5/1.5 Sn, 0.5 Mn, bal. Zn
Aluminum bronze (5%)	92	55	65	22	7	65					15	B92	B35	1920	0.285	17.5	Strip (also rod, forgings, tube) good hot and cold forming but limited drawing	92/96 Cu, 4/7 Al, 0.5 Fe max
Aluminum bronze (8%)	105	65	64	26	7	60					17.5–19	B96	B50	1890	0.274	14.8	Sheet (bar, forgings, extrusions) good resis. to corrosion, tarnishing, wear and heat, with good mech properties	92 Cu, 8 Al nominal
Cupro nickel (30%)	75	55	70	20	15	45					22	B80	B35	2140	0.323	4.6	Sheet, tube and rod (rod ½ hard and tube annealed) very good corrosion resistance, forming and mech. properties for condenser tubes, etc.	29/33 Ni, bal. Cu
Hardenable by heat treating																		
Beryllium copper (sol. treated and precip. hardened)	19b	72	110	25	3	50			41	32	20–17	C42.5	B60	1587	0.297	21–17	Strip (and rod). Good formability, strength, conductivity, corr. and wear resis. For many uses, even at high price	1.9/2.15 Be, 0.15/0.50 Ni, bal. Cu
Chromium copper (precip. hardened)	72–63		61–45		25							B77–65		1975	0.32	80	Rod. Moderate strength and fatigue resistance with excellent conductivity	0.85 Cr, 0.05 Si, 99.1 Cu nominal

* SAE and ASTM designations or suppliers' identifications are often used in place of these terms.

Table 8.4 Typical Properties of Representative Cast Copper Alloys

Designation *†	Tensile Strength, M psi	Yield Strength 1/2% Offset, M psi	Elongation in 2 in., %	Shear Strength 0.1% Set, M psi	Compress. Strength 0.001% Set, M psi	Mod. of Elasticity, 10^6 psi	Hardness, Brinell, 500, 10	Density, lb cu in (68 F)	Electrical Conductivity, % IACS (77 F)	Uses	Composition, %
Leaded tin bronze (Navy M)	38	16	35	34	13	13	66	0.315	14	High-grade steam or valve bronze to 550 F, moderate pressures†	86/90 Cu, 5 5/6 5 Sn, 1/2 Pb, 3/5 Zn
Leaded tin bronze (G)	36	18	30	43	13	14	68	0.318	11	High-duty, wear-resistant bearing bronze	85/89 Cu, 7.5/9 Sn, 3/5 Zn, 1 Pb
Leaded tin bronze, high lead, tin	32	17	12	43	14 5	11	65	0.32	..	Bearings for high speeds and pressures	78/82 Cu, 9/11 Sn, 8/11 Pb
Leaded brass, red	32	15	24	29	11.5	13	55	0.312		General-purpose free machining for plumbing and other fittings	78/82 Cu, 3.25/4 Sn, 5/7 Pb, 5/8 Zn
Leaded brass, semired	32	15	22		12	13	55	0.314	18	Ornamental and low-pressure valves and fittings	78/82 Cu, 2.25/3 Sn, 6/8 Pb, 7/10 Zn
Leaded brass, yellow	35	12	35	30	9	13	48	0.307	25	General-purpose, hardware, trim, fittings and ornamental	70/74 Cu, 0.75/2 Sn, 1 5/3.75 Pb
Leaded brass, yellow	40	14	25			14	65	0.304	20-26	General-purpose valves, hardware, and ornamental trim	60/65 Cu, 0.5/1.5 Sn, 0.75/1.5 Pb
Leaded brass, nickel silver	34	15	20	.			60	0.323		Hardware, plumbing fixtures, statuary, ornaments	53/58 Cu, 1.5/3 Sn, 8/11 Pb, 11/14 Ni, bal. Zn
Manganese bronze, standard	70	28	30	87	24	15	125	0.296	18	Tough and strong grade for propeller blades, and parts contacting water, levers, stems, etc.	58 Cu, 39.25 Zn, 1.25 Fe, 1.25 Al, 0.25 Mn nominal
Manganese bronze, high strength	115	70	15	100	60	15.5	210	0.285	12	Toughness and hardness for extra-heavy-duty gears, covers, valve stems, slow-speed bearings, etc.	60/68 Cu, 3/7 Al, 2.5/5 Mn, 2/4 Fe, bal. Zn
Silicon bronze	45-55	18-30	20-30		15-22		80-130			High strength, toughness, and corrosion resistance	90/95 Cu, 4 Si, Fe, Al, Zn nominal
Aluminum bronze (9% Sn) as cast	75	27	35	67	29	17	120	0.267	13	High strength, toughness, hardness, and corrosion resistance for marine equipment, acid pump parts, bearings, gears, valve seats, guides, etc.	88 Cu, 3 Fe, 9 Al
Aluminum bronze (11% Sn)	110	65	5			18	250	0.271	13		89 Cu, 4 Fe, 11 Al nominal
Solution treat 1600-1650, water quench and age, 1 hr at 1000 F	92	50	15				195	.	14		89 Cu, 1 Fe, 10 Al nominal

* SAE, ASTM, and suppliers' identifications are also used in place of these terms.

† General properties:

Thermal conductivity, % of Cu approx equals electrical volume conductivity. Coefficient thermal expansion is approx $9\text{-}12 \times 10^{-6}/°F$ for 70-400 F. Melting points range from 1570-1800 F.

phase (see Fig. 8.4). They are easily cold worked, and their ductility increases with increase in zinc to a maximum at 36 per cent zinc, 64 per cent copper. With more than 36 per cent zinc, the brittle "beta" phase appears along with the alpha, making the alloy increasingly difficult to cold work. The high zinc brasses are therefore most easily *hot* worked, whereas the lower zinc brasses (alpha brasses) are formed more easily while *cold*.
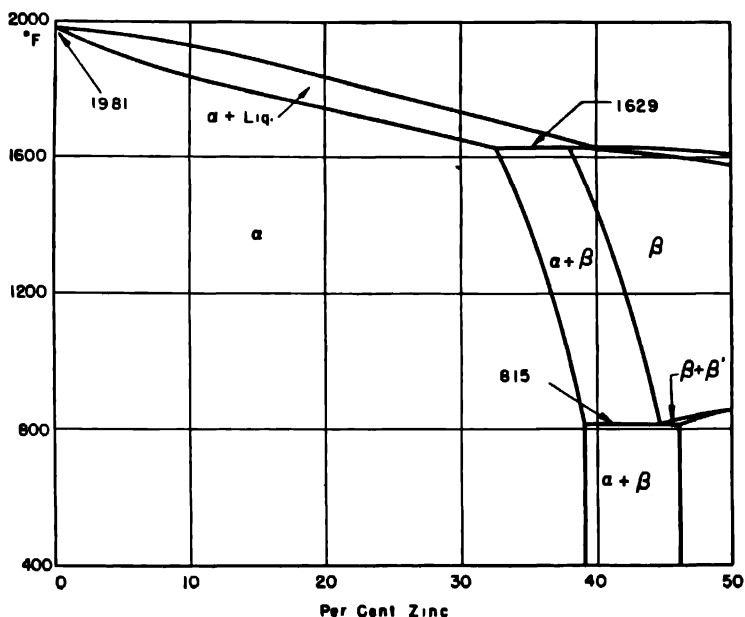
Fɪɢ. 8.4. Constitution diagram of copper-rich portion of copper-zinc alloy system.

All the brasses containing up to 40 per cent zinc are useful, and there are dozens of varying compositions. Slight modifications of composition usually do not produce important changes in properties. For the purpose of discussion, the common alloys are divided into groups. The names of the alloys in each group are generally unrelated, but they are used by custom throughout the trade.

8.15 BRASS CONTAINING 5 TO 15 PER CENT ZINC

Brasses containing up to 15 per cent zinc have good corrosion resistance. Like copper, they are ductile and suitable for extreme cold working, but are difficult to machine. Gilding brass (5 Zn)

and commercial bronze (10 Zn) are used for bullet jackets and articles exposed to the weather. Color is often the basis of selection between them. Gilding brass is nearly copper colored; commercial bronze has a true "bronze" color. Red brass (15 Zn), also called "rich ,low brass," is used for imitation gold jewelry. It has the best corrosion resistance of all the brasses and is superior to copper for handling hard water, and is consequently used for plumbing hardware, pipe, radiator cases, and condenser tubing.

8.16 BRASSES CONTAINING 20 TO 36 PER CENT ZINC

Brasses containing between 20 and 36 per cent zinc are very readily cold worked. Their advantages over brasses containing less zinc lie in low cost, since zinc is cheaper than copper, and in superior machinability. Brasses containing 20 to 36 per cent zinc can also be hot worked, but only if their constituents are very pure. This is a new development, since high-purity zinc must be used and it has not been available commercially in the past.

The medium-zinc brasses are subject to corrosion which works in either of two ways. When exposed to acids or salt solutions (such as hard water), zinc may be removed electrolytically. This dezincification leaves spongy layers of copper, often called plugs, on the surface. Under the influence of corrosive media and stress, brasses with more than 15 per cent zinc fail by season cracking, sometimes called corrosion cracking. The failure occurs in areas where stress is maximum; and to minimize the danger of failure, stresses remaining after cold working should be relieved by annealing. In service, however, load stresses can scarcely be avoided. According to recent tests the load stress which eventually produces season cracking is very much less than the yield stress.

Brass with 20 per cent zinc, called low brass, has fair corrosion resistance, being subject to dezincification and season cracking under only the most severe conditions. Both low brass and brazing brass (25 Zn) are deep drawn, spun, and cold formed with ease. They are used for musical instruments, drawn eyelets, and for ornamental architectural work. Brass containing 30 per cent zinc is very tough and ductile, since it is high in zinc. It is particularly suited to deep drawing or spinning and is usually called *cartridge brass*. In the past, cartridge cases were manufactured entirely by cold working. Today, however, a high-purity grade of zinc is used, as mentioned above, and hot working in the initial forming of the

part is employed, thus avoiding repeated cold working and annealing cycles.

The substitution of 1 per cent tin in cartridge brass produces a grade known as Admiralty metal. The usual composition is 70 copper, 29 zinc, 1 tin, with as much as 0.05 per cent arsenic, which tends to inhibit dezincification. The tin gives the alloy fair resistance to corrosion by sea water and has led to its use in marine condenser tubing.

An alloy containing 76 Cu, 22 Zn, 2 Al, *aluminum brass*, forms a tenacious surface film in contact with water. It has been used for condenser tubing, particularly where the alloy must withstand erosion by high velocity water.

The 34 per cent zinc brass, known as common high brass, and yellow brass, is the cheapest of all the brasses that may be cold worked. Large quantities of screws, rivets, and tubing are made of high brass, although it is subject to corrosion. Parts that are cold formed should be annealed after the final forming to inhibit season cracking.

8.17 BRASSES CONTAINING 36 PER CENT OR MORE ZINC

Brasses containing more than 36 per cent zinc contain the brittle beta phase and are difficult to cold work. They may be hot worked, however. Muntz metal (40 Zn) is worked at a red heat and is not malleable when it is cold. It is used only in mildly corrosive media, and then principally because of its low cost.

The addition of a small amount of tin (40 Zn, 0.75 Sn, balance Cu) to Muntz metal produces the composition called Naval brass. As with Admiralty metal, the tin is added to give resistance to corrosion by sea water.

Extrusion is used not only for tubing, but for many irregular shapes. Brasses that are easily hot worked are often extruded when hot, whereas others are extruded cold. The hot-extruding alloys are most often used, however, because the power used in extrusion is a minimum. An alloy that has excellent plasticity at high temperature contains 37 per cent zinc and 4 per cent lead.

Up to 3 per cent lead is often added to brass to improve machining properties, because it causes the chips to break free. Where it is necessary to do severe cold forming and machining on the same part, 1 per cent lead may be used, since a 3 per cent lead brass would be easily broken in cold forming. An alloy that is easily hot worked and machined is forging rod (38 Zn, 2 Pb, 60 Cu). Lead in these

percentages does not affect the corrosion resistance or conductivity of brass.

Brasses containing over 40 per cent zinc are not widely used. One application is as a brazing spelter of half-and-half composition (50 Zn, 50 Cu).

Practically no straight brasses, that is, plain copper and zinc alloys, are used for castings. Some of the complex brasses, primarily those with the addition of manganese and other elements, are used in quantity for castings. Scrap brass is often cast, however, if accurate control of the properties is unnecessary.

8.18 BRONZES NOT HARDENABLE BY HEAT TREATMENT

Alloys of copper with materials other than zinc are usually called bronzes, although application of the term is loose, as indicated by the brass called "commercial bronze." Like the copper-zinc alloys, the bronzes may be hardened by cold working. Some of the bronze alloys can be also hardened by precipitation heat treatment.

Silicon Bronze. Silicon bronze has an average composition of 96 per cent copper, 3 per cent silicon, and 1 per cent manganese or zinc. It has the good general corrosion resistance of copper, combined with higher strength, and in addition can be cast, rolled, spun, stamped, forged, and pressed either hot or cold and can be welded by all the usual methods. Common uses are parts for boilers, tanks, stoves, or wherever high strength and good corrosion resistance are required. It is exceptionally easy to weld by any common method, but the silicon content tends to make it difficult to solder and braze. Duronze, Olympic, Everdur, and Herculoy are trade names.

Phosphor Bronze. Copper-tin alloys deoxidized with phosphorus are called either tin bronze or phosphor bronze. The range of tin is from less than 1 per cent to 11 per cent, and the phosphorus ranges from an almost negligible amount up to 0.5 per cent. Strength and hardness increase with tin content, but so does the cost. The tin bronzes have high strength, resilience, and resistance to wear and fatigue. These properties recommend them particularly for use as a spring material. Up to 4 per cent lead may be added to improve machinability. Shafts and bushings with moderately good wear resistance are made of the free-machining (leaded) phosphor bronze.

Cupro-Nickels. Copper and nickel form a complete series of solid solutions, and show no sudden change in properties with change in composition. Alloys with 20 to 30 per cent nickel are used under severely corrosive conditions. Large quantities are used for tubing

in oil field applications and for marine condensers. Although nickel is an expensive alloying agent, its use is often justified because of the superior resistance of its alloys to corrosion.

An alloy of 45 per cent nickel, called Constantan, has high electrical resistance and low temperature coefficient of resistance, qualities which make it an ideal material for electrical-resistance wire. Its high thermoelectric force when in contact with other common metals also makes it a good thermocouple material.

Nickel silver contains zinc, in addition to copper and nickel. Although there are many variations in composition, an alloy containing 64 copper, 18 nickel, and 18 zinc is by far the most widely used. It has a silvery color, good corrosion resistance, and fairly high electrical resistivity. Nickel silver is used as a base for plated jewelry and tableware, for ornamental metal work, food-handling equipment, marine fittings, and for electrical resistance wire and springs.

8.19 BRONZES HARDENABLE BY HEAT TREATMENT

A few of the alloys of copper can be hardened upon quenching as steel is hardened. Most are hardened by solution heat treatment and precipitation aging.

Aluminum Bronze. Aluminum bronze is a versatile alloy since its properties may be controlled over a wide range, not only by variation of alloying agents, but also by heat treatment.

With up to 7.5 per cent aluminum, the copper-aluminum alloys are extremely ductile. When a metal must be severely cold worked, aluminum bronze is often substituted for brass because of its superior strength and resistance to corrosion. An alloy of 7.5 to 9.5 per cent aluminum and up to 1.5 per cent iron with copper is used as cast, without hardening, for good corrosion and shock resistance. Increase of aluminum to 12 per cent and iron to 4 per cent provides an alloy which, in the as-cast condition, has a very high endurance limit and resistance to shock. It is used for heavily loaded gears in machine tools, steel mill drives, and construction machinery. Cams, rollers, and slides utilize its excellent resistance to wear. Aluminum bronze high in aluminum (9.5 to 12 per cent) and iron (1.5 to 4 per cent) may be hardened to a degree comparable with the alloy steels, yet may have superior resistance to abrasion. Though brittle, it is valuable in such parts as dies and sliding machine members. Hardening of the 10 per cent aluminum alloy occurs upon quenching from 900 C. Greater toughness can be restored by annealing to 550–700 C and requenching.

Beryllium Bronze. Beryllium bronze (beryllium copper) is a precipitation-hardening alloy usually composed of about 2 per cent beryllium and the remainder copper. It is usually solution heat treated and cold worked to some extent by the supplier before fabrication by forming and machining. It may be hardened by aging in a furnace for several hours at 500 to 600 F. When hard, it has better wear resistance than phosphor bronze. Heavily loaded bushings, seats, or springs subject to vibration or shock are usually made of beryllium bronze, even though it is relatively expensive. The springs have a remarkable freedom from hysteresis and elastic drift and retain their springiness to a greater degree than springs of any other corrosion-resistant material.

Chromium Bronze. Chromium bronze is a precipitation-hardening alloy of copper with up to 1 per cent chromium. It has not as yet been used in large quantities but has high electrical conductivity and high temperature resistance.

Magnesium

8.20 CHARACTERISTICS

This metal is produced in the United States from sea water. Magnesium hydroxide from the sea water is precipitated with calcium oxide, filtered, and then neutralized with hydrochloric acid. The resulting magnesium chloride is dried, melted, and reduced to the commercially pure form by electrolysis. During World War II some magnesium was produced by forming the oxide, and then causing reduction by heating with carbon or silicon.

Magnesium is the lightest of the commercial metals; its density is about two-thirds that of aluminum, one-fourth that of steel. Pure magnesium is seldom used as a structural material because of its low strength, but its alloys are stronger and many of them can be hardened by precipitation heat treatment. The uses for magnesium in alloys for portable or high-speed machinery have multiplied and its price has dropped correspondingly. The price is close enough to aluminum that magnesium competes with aluminum in many applications.

The strength-to-weight ratio of the precipitation-hardened magnesium alloys is comparable with that of the strong alloys of aluminum or with the alloy steels. Magnesium alloys, however, have a lower density and stand greater column loading per unit weight.

They are also used when great strength is not necessary, but where a thick, light form is desired. Examples are complicated castings, such as housings or cases for aircraft, and parts for rapidly rotating or reciprocating machines. The strength of magnesium alloys is reduced at somewhat elevated temperatures; temperatures as low as 200 F produce considerable reduction in the yield strength.

Despite the active nature of the metal, magnesium and its alloys have good resistance to corrosion by most atmospheres. In industrial or humid areas, however, corrosion is most rapid and will, over a period of years, cause powdering of the surface. The rate of corrosion is slow compared with the rusting of mild steel in the same atmosphere. Immersion in salt water is very dangerous, but a great improvement in resistance to salt-water corrosion has been achieved, especially for wrought materials, by reducing some impurities, particularly nickel and copper, to very low proportions. Corrosion troubles may be expected even with protective treatment in poorly designed assemblies where moist air is trapped or where rain is allowed to collect. Where such designs are avoided, unpainted magnesium alloy parts that are oily or greasy will operate indefinitely with no sign of corrosion. Magnesium alloy parts are usually painted, however, except where the conditions of exposure are mild. To assure proper adherence of the paint, the part is cleaned by grinding, buffing, or blasting, then given an acid dichromate dip.

8.21 FABRICATION

Hot and Cold Working. Magnesium alloys harden rapidly with any type of cold work, and therefore cannot be extensively cold formed without repeated annealing. Sharp bending, spinning, or drawing must be done at about 500 to 600 F, although gentle bending around large radii can be done cold. Slow forming gives better results than rapid shaping. Press forging is preferred to hammer forging, because the press allows greater time for metal flow. The plastic forging range is 500 to 800 F, and if the metal is worked outside this range it will be easily broken.

Casting. The magnesium alloys, especially those which may be precipitation hardened, are used in casting. Sand, permanent-mold, and die-casting methods may be used, but plaster-of-Paris casting has not yet been perfected.

Sand casting in green-sand molds requires a special technique, because the magnesium will react with moisture in the sand, forming magnesium oxide and liberating hydrogen. The oxide forms black-

ened areas called *burns* on the surface of the casting, and the liberated hydrogen may cause porosity. Inhibitors such as sulfur, boric acid, ethyl glycol, or ammonium fluoride are mixed with the damp sand to prevent the reaction. All gravity-fed molds require an extra high column of molten metal so the pressure will be great enough to force gas bubbles out of the casting and cause the metal to take the detail of the mold cavity. The thickness of the casting wall should be at least $\frac{5}{32}$ in. under most conditions. Extra-large fillets must be provided at all re-entrant corners, since stress concentrations in magnesium castings are particularly dangerous.

Permanent mold castings are made from the same alloys and have about the same physical properties as sand castings. Since the solidification shrinkage of magnesium is about the same as that of aluminum, aluminum molds can often be adapted to make magnesium-alloy castings (although it may be necessary to change the gating).

Pressure cold-chamber castings are used for quantity production of small parts. The rapid solidification caused by contact of the fluid metal with the cold die produces a casting of dense structure with excellent physical properties. The finish and dimensional accuracy are very good, and machining is necessary only where extreme accuracy is required. Usually these castings are not heat treated.

Welding, Soldering, and Riveting. Many of the standard magnesium alloys are easily welded by gas or resistance-welding equipment, but they cannot be cut with the oxygen torch. Magnesium alloys are not welded to other metals, because brittle intermetallic compounds may form, or because the combination of metals may promote corrosion. Where two or more parts are welded together, their compositions should be the same.

Soldering of magnesium alloys is feasible only for plugging surface defects in parts. The solders are even more corrosive than with aluminum, and should never be required to withstand stress.

Riveted joints in magnisum alloy structures usually employ aluminum or aluminum-magnesium alloy rivets. Magnesium rivets are not often used because they must be driven when hot. Where aluminum alloy rivets are used under corrosive conditions, the rivet should be dipped in a bitumastic paint to insulate it from the magnesium. The rivet holes should be drilled, especially in heavy sheet and extruded sections, since punching tends to give a flaky structure at the edge of the hole and to cause stress concentrations.

Machining. Magnesium and its alloys have the best machining characteristics of the common metals. The power required in cut-

ting them is small, and extremely high speeds (5000 ft per min in some cases) may be used. The best cutting tools have special shapes, but the tools for machining other metals can be used, although somewhat lower efficiency results.

When magnesium is cut at high speed, the tools should be sharp and should be cutting at all times. Dull, dragging tools operating at high speed may generate enough heat to ignite fine chips. Since chips and dust from grinding can therefore be a fire hazard, grinding should be done with a coolant, or with a device to concentrate the dust under water. The magnesium grinder should not be used also for ferrous metals, since a spark might ignite the accumulated dust. If a magnesium fire should start, it can be smothered with cast-iron turnings or dry sand, or with other materials prepared especially for the purpose. Water or liquid fire extinguishers should never be used, because they tend to scatter the fire. Actually, it is much more difficult to ignite magnesium chips and dust than is usually supposed, and for that reason they do not present great machining difficulties.

The special techniques that must be used in fabricating magnesium (working, casting, joining) add considerably to the manufacturing cost. In selecting between aluminum and magnesium for a given part, the base cost of the metal may not give much advantage to either, but usually the manufacturing operations will make magnesium the more expensive.

8.22 ALLOYS OF MAGNESIUM

Practically all the commercial magnesium alloys manufactured in the United States contain aluminum (3 to 13 per cent) and manganese (0.1 to 0.4 per cent). Many also contain zinc (0.5 to 3 per cent) and some are hardenable by heat treatment.

The composition, forms, uses, and typical properties of representative alloys are given in Table 8.5. Minimum property values are somewhat lower than those listed. All the alloys may be used for more than one product form, but alloys AZ63 and AZ92 are most used for sand castings, AZ91 for die castings, and AZ92 for most permanent mold castings (AZ63 and A10 are sometimes used). For forgings, AZ61 is most used, with M1 employed where low strength is required and AZ80 for highest strength. For extrusions, a wide range of shapes, bars, and tubes is made from M1 alloy where its low strength suffices or where welding to M1 castings is planned. Alloys AZ31, AZ61, and AZ80 are employed for extrusions in the order named, where their increase in strength justifies their increased cost.

Table 8.5   Typical Properties of Representative Magnesium Alloys

Designation*	Tensile Strength, M psi	Yield Strength 0.8% Offset, M psi	Elongation in 2 in., %	Hardness, Brinell, 500/10	Shear Strength, M psi	End. Limit 500×10^6 Cycles Rev. B., M psi	Electrical Conductivity, % Cu	Uses	Nominal Composition, %
Pure magnesium—Sand cast	12	3	6	30	17		38.6	Sheet, wire, extrusions, ribbon, and powder for deoxidizers, vacuum getters, pyrotechnics, and dry rectifiers	99.8% Mg min
Annealed	27	14	16	40		9			
Hard-rolled sheet	37	27	9	50	18	11	15		
A263—As cast	29	14	6	50	19	14	12.3	Sand and permanent mold castings—general purpose alloy with good strength and best ductility and toughness (Dow H) (AM 265)	5.3/6.7 Al, 2.5/3.5 Zn, 0.15 min Mn, bal. Mg
Solution treated, air cool from 735 F	40	14	12	55			13.8		
Aged 375, 18 hr	40	19	5	73	20	13	13.8		
A262—As cast	25	14	2	65	18	12	12.3	Sand and permanent mold castings of highest strength, hardness, and pressure tightness (Dow C) (AM 260)	8.3/9.7 Al, 1.6/2.4 Zn, 0.1 min Mn, bal. Mg
Solution treated	40	14	10	63	20	13	10.5		
Aged	40	22	3	81	22	12	12.3		
A261—As die cast	33	22	3	60	20	14	10.1	The most generally used magnesium die-casting alloy (Dow R) (AM 263)	8.3/9.7 Al, 0.4/1 Zn, 0.2 Mn, bal. Mg
M1—Sheet, annealed	33	18	17	48	17	9	34.5	Low cost alloy of moderate mechanical properties, good weldability, and hot workability. Castings of same alloy available for welding to wrought parts (Dow M) (AM 3S)	1.2 min Mn, bal. Mg
Sheet, hard	35	26	7	54	17	10			
Forged	36	23	7	47	16				
Extruded †	(35–38)	(23–28)	(8–11)	(42–46)	16	9			
AZ31X—Sheet, annealed	37	22	21	55	21	11	18.5	Low cost alloy with high corrosion resistance and best forming qualities as sheet and plate (Dow FS-1) (AM 52S)	2.5/3.5 Al, 0.6/1.4 Zn, 0.2 min Mn, bal Mg
Sheet, hard	42	33	11	72	23	13	18.5		
Extruded †	(35–40)	(22–30)	(15–18)	50	19	15			
AZ61X—Press forged	43	26	12	55	21	16	11.6	General purpose alloy for extrusions and forgings of intermediate cost (Dow J-1) (AM 57S)	5.8/7.2 Al, 0.4/1.5 Zn, 0.15 min Mn, bal. Mg
Extruded †	(40–45)	(22–32)	(15–16)	(55–60)	20	17			
AZ80X—As forged	46	31	8	69	22	18	14.6	Highest strength wrought alloy, hardenable by heat treatment. Used for forgings and extrusions (Dow O-1) (AM 58S)	7.8/9.2 Al, 0.2/0.8 Zn, 0.10 min Mn, bal. Mg
Forged and aged	50	34	6	72	23	16	10.6		
As extruded	49	35	12	63	21	19	14.6		
Aged	50	36	7	80	22	19			
Heat treated and aged	53	40	7	80	22				

* Designations are ASTM. Dow and American Magnesium cross references are given under "Uses."

† Variations in properties of extrusions depend on form. Bar usually has highest strength, shapes max ductility, tube intermediate.

Other properties are approximately:
Specific heat, 0.25 /C cal./Gm.
Mod. of elasticity, 6,500,000 psi.
Mod. of rigidity, 2,400,000 psi.
Poisson's ratio, 0.35.
Coefficient of thermal expansion, 26×10^{-6} /C from 20–100 C.
Density, 0.064–0.066 for alloys, 0.0628 for commercially pure.
Machinability index, 500, based on brass free-cutting at 100
Recrystallization temp, cold work, 350 to 600 F.
Hot-working range, 450–900 F.
Melting point, 1100–1200 F.

Nickel and Nickel Alloys

8.23 CHARACTERISTICS

Although some nickel is obtained commercially from oxide ores, arsenical ores, and the ores of copper, manganese, and iron, at least 85 per cent of all nickel production is obtained from sulfide ores, particularly those of Canada and Norway. The refining process for the latter involves grinding, classification, roasting, and smelting to remove sulfur. Iron is eliminated in a Bessemer converter and the resulting nickel-copper matte is then charged with alkaline sulfide flux into a blast furnace. The product cast from the blast furnace solidifies into two layers. The top layer contains copper sulfide; the bottom layer contains nickel sulfide. The bottoms are crushed, leached, sintered, melted, and cast into anodes. Electrolytic refining of the anode cakes in a continuously purified nickel-sulfate electrolyte results in cathode nickel of 99.95 per cent purity, except for retained cobalt of 0.3 to 0.5 per cent.

Pure nickel is a tough, silver-colored metal, with about the same density as copper, but with 3 times its cost. The properties for which nickel is distinguished are oxidation and corrosion resistance, especially at high temperature, and the ability to form many alloys. Large quantities are used as an alloying element in steel (see Chapter 7) and in copper alloys. The applications for nickel, and the approximate percentage of the annual production used for each in 1939, are listed in Table 8.6. Figures indicating expanded use of nickel for military equipment are not available for the war or postwar periods.

Table 8.6 Uses of Nickel in the United States *

Application	Per Cent
Wrought and cast alloy steels	60
Alloy cast irons	4
Nickel—copper alloys and nickel silvers	14
Nickel brass, bronze, and aluminum alloys	2
Nickel cladding, coinage, rolled nickel	9
Nickel electroplating	6
Electrical-resistance alloys	3
Miscellaneous	2

* From *Metals Handbook*, 1948 edition, Am. Soc. Metals data for 1939.

Although pure nickel and alloys high in nickel are used in small quantities, it would be difficult to do without them entirely. Their

excellent properties persist even at high temperatures, where many other metals become weak or plastic and oxidize rapidly. The oxidation of nickel usually is not dangerously rapid below 1200 to 1400 F, and many nickel parts are operated in even hotter oxidizing atmospheres. At 1800 to 2200 F, however, nickel is subject to a peculiar intercrystalline brittleness if exposed to oxidizing or sulfurizing gases. The pores of the surface grains are oxidized or sulfurized, producing a brittle surface layer that cannot be deformed by subsequent drawing or forming operations. The presence of fine surface cracks indicates that the atmosphere during heating was unsatisfactory. Where the metal must, in service, withstand such high temperatures and oxygen or sulfur atmospheres, impure grades of nickel, containing up to 5 per cent manganese, are used.

At normal temperatures nickel is ferromagnetic; however, at 780 F and above it becomes paramagnetic. Many of the applications classed as miscellaneous in Table 8.6 involve the ferromagnetic properties of nickel and its alloys. Some of the nickel alloys are used for their high potential field strengths, some for their high permeability, and some for their high coercive force (see Chapter 6).

8.24 FABRICATION

The casting of nickel and its alloys requires some special technique, since they are poured at a high temperature (about 3350 F for Monel). Working is done successfully, but the high-nickel materials work harden more rapidly than low-carbon steel, copper, brass, aluminum, and aluminum-base alloys. In general, fabrication methods are more similar to those used for steel than for the softer nonferrous materials. Heavier equipment is required for cold forging, deep drawing, and spinning, and the materials must be annealed more frequently during the cold-working operations. In the hot-working operations, the high melting points of the nickel materials require temperatures that are practically identical with those used for steel and, in addition, atmospheres that are sulfur free, because of the embrittling effect of this element upon nickel. Annealing temperatures for all the high-nickel materials except pure nickel are considerably higher than those required for steel. Bright annealing is easier than with steel because the nickel materials oxidize less readily. The procedure for age hardening is essentially the opposite of that for steel; the nickel materials are soft when quenched from high temperatures and are hard when held at, and cooled from, intermediate temperatures. The

different physical and mechanical characteristics of the nickel materials require slight modifications in welding to insure adequate fusion and penetration and to prevent buckling. Resistance welding requires less current because of the high electrical resistivity that is associated with most high-nickel alloys, particularly those containing chromium and molybdenum.

The high-nickel materials are not difficult to machine, although combinations of tools, speeds, feeds, and cutting compounds different from those used with steel or brass are required. The methods for shearing, perforating, and tube and pipe fabrication require but little modification of the standard technique for steel. Pickling is quite different because the high-nickel materials are strongly resistant to many acids, particularly those used for steel and the high-copper alloys.

8.25 MONEL ALLOYS

The most important of the commercial nickel alloys is Monel metal, which is produced directly by removing impurities from a natural ore, and is consequently cheaper than pure nickel. Monel has the average composition 67 per cent nickel, 28 per cent copper, and 5 per cent iron, manganese, and silicon combined.

The resistance of Monel to steam attack at high temperatures has caused its extensive use in steam valves and turbine blading. Such parts may be subjected to severe erosion by unsaturated steam in which the drops of water may be traveling at velocities as high as 1000 ft per sec. Few materials are capable of enduring the impact of these drops as well as Monel. It is suitable for use in steel machinery that operates over a wide temperature range, since the thermal expansions of Monel and steel are approximately equal. Where steel shafting does not have the required resistance to corrosion, Monel may be used instead; it has wear-resistant qualities as good as steel, if used with the correct bearings.

Of all the structural nonferrous metals, Monel has the best resistance to weakening at high temperatures. At 750 F it retains 75 per cent of its room-temperature tensile strength, proportional limit, and elongation, and its modulus of elasticity is changed very little. Recrystallization begins at 800 F, but full annealing cannot be expected below 1200 F, and even then the annealing time is too slow to be commercially useful. Monel resists oxidation at 1350 F, but

Table 8.7 Typical Properties of Representative Nickel Alloys *

Designation†	Tensile Strength, M psi	Yield Strength 0.2% Offset, M psi	Elongation in 2 in., %	Hardness, Brinell, 500/10	Impact Strength, Ft-lb		Density, lb/cu in.	Mod. of Elasticity, 10^6 psi	Thermal Conductivity, Btu/hr (ft² F/in.)	End. Limit 100×10^6 Cycles R.R., M psi	Nominal Composition, %	Uses
Cast Materials												
Nickel	45–60	20–30	30–15	80–125	90–75	120D	0.302	21.5	410	.	99.4 Nickel	Resistance to corrosion and oxidation
Monel	65–90	32–40	45–25	125–150	80–65	120D	0.312	18.5	180		67 Ni, 30 Cu, 1.4 Fe, 1 Mn	Strength and resistance to corrosion
H monel	90–115	45–75	20–10	175–250	45–35	120D	0.307	20	180		65 Ni, 29.5 Cu, 1.5 Fe, 0.9 Mn, 3 Si	High hardness compared to monel
S monel	110–145	80–115	4–1	275–375	9–1	120D	0.302	21	180	..	63 Ni, 30 Cu, 2 Fe, 0.9 Mn, 4 Si	Age hardenable. Resists galling and erosion
Inconel	70–95	30–45	30–10	160–190	85–70	120D	0.30	22.7	.	..	78.5 Ni, 0.2 Cu, 6.5 Fe, 14 Cr	Strength, resists corrosion and oxidation
60 Ni-15 Cr	60–70	40–60	5–2	170–210	..		0.308	30–31	95–100	..	62–54 Ni, 12–16 Cr, 1/1.5 Si to 1 Mn, bal. Fe	Strength and resistance to oxidation
Hastelloy A	69–78	43–45	12–8	155–200	35–25	120D	0.318	27	116	..	57 Ni, 20 Fe, 20 Mo, 2 Mn, 1 Si	Age hardenable, strength, resists hydrochloric and sulfuric acids
Hastelloy B	76–82	55–57	9–6	190–230	16–11	120D	0.334	30.8	78	..	62 Ni, 6 Fe, 30 Mo, 1 Mn, 1 Si	Age hardenable, resists boiling HCl and wet gas
Hastelloy C	72–80	45–48	10–15	175–215	14–9	120D	0.323	28.5	87	..	55 Ni, 6 Fe, 17 Mo, 15 Cr, 1 Mn, 1 Si	Age hardenable, resists strong oxidizing acids
Illium G	60–73	50–63	9.5–4	160–210	..		0.301	.	.	..	58 Ni, 8 Cu, 6 Fe, 22 Cr, 6 Mo, 1.25 Mn, 0.65 Si	Strength, resists nitric and sulfuric acids
Wrought materials												
Nickel	60–165	15–155	50–2	90–230	Charpy 222–195 / 240–36	120D / 120D	0.322	30	420	23–36	99.4 Ni	All wrought forms for resistance to corrosion and oxidation
"Z" nickel	90–250	30–150	50–2	140–380	..		0.317	30	420	52–59	98.0 Ni	Rod, bar, wire, strip. Age hardenable, high strength—springs
Monel	70–170	25–160	50–2	110–250	220–150	120D	0.32	26	180	30–50	67 Ni, 30 Cu, 1.4 Fe, 1 Mn	All wrought forms for strength and corrosion resistance
K monel	90–200	40–175	45–2	140–320	170–42	120D	0.307	26	130	41–59	66 Ni, 29 Cu, 2.75 Al, 0.9 Fe, 0.85 Mn, 1 Si	All forms but sheet. Age hardenable—nonmagnetic high-strength springs
KR monel	90–200	40–175	45–2	140–320	..		0.307	26	130	.	66 Ni, 29 Cu, 2.75 Al, 0.9 Fe, 0.85 Mn, 1 Si	Rod, bar, and wire. Age hardenable, free machining
90 Ni-20 Cr	100–200	50–190	35–0.5	170–300	..		0.305	.	104	.	20 Cr, 1.25 Si, 0.2 to 2 Mn, 0.5 Fe, bal. Ni	All wrought forms. Resis. to oxidation—electric heating units
Inconel	80–185	25–175	50–2	120–290	230–151	120D	0.308	31	104	41–60	78.5 Ni, 14 Cr, 6.5 Fe	All wrought forms. Strength, resis. corrosion and oxidation—springs and heat-treating equip.
60 Ni-15 Cr	80–175	40–160	35–0.5	180–235	..		0.311	31	95–100	..	62–54 Ni, 12–16 Cr, 1 to 1.5 Si, to 1 Mn, bal. Fe	All wrought forms. Strength, resistance to oxidation
Hastelloy A	110–120	47–52	48–40	200–215	77–62	120D	0.318	27	116	..	57 Ni, 20 Fe, 20 Mo, 2 Mn, 1 Si	All wrought forms. Age hardenable, see cast
Hastelloy B	130–140	60–65	45–40	210–235	79–68	120D	0.334	30.8	78.5	..	62 Ni, 6 Fe, 30 Mo, 1 Mn, 1 Si	All wrought forms. Age hardenable, see cast
Hastelloy C	115–128	55–65	50–25	160–210	40–34	120D	0.324	28.5	87	..	55 Ni, 6 Fe, 17 Mo, 15 Cr, 1 Mn, 1 Si	Sheet, strip, and tube. Age hardenable, see cast

* Properties are listed in ranges typical of annealed to hard-worked metal for solution-alloy types, and for annealed or solution treated to high strength. Precipitation aged for age-hardenable types. Age-hardenable alloys are noted under "Uses."

† Designations are from the International Nickel Co. or the Haynes-Stellite Co.

it is not recommended for use above 1450 F, since nickel is superior at such temperatures.

The color of Monel is very nearly the same as that of nickel; this property, together with its good corrosion resistance and lower cost, has brought about its use in kitchen utensils and appliances, and in laundry and dairy machinery.

K—Monel * has the same composition as Monel, except that it contains 2 to 4 per cent added aluminum. It can be hardened by precipitation heat treatment, and it has good corrosion resistance and strength at high temperature.

H—Monel * and S—Monel * are made by adding 3 and 4 per cent silicon, respectively, to Monel. They have good casting characteristics and can be hardened by precipitation heat treatment. S—Monel is very hard and does not gall. Because of its wear resistance, it is used in cast pistons, bearings, and valve seats.

Monel can be made easy to machine by addition of 0.35 per cent sulfur. This free machining alloy is called R—Monel.*

8.26 INCONEL

Inconel is an alloy of 80 per cent nickel, 14 per cent chromium, and 6 per cent iron. It has extremely good resistance to oxidation and corrosion in some applications, and has an impact strength better than that of any of the steels.

8.27 ALLOYS WITH SPECIAL ELECTRICAL PROPERTIES

Nickel alloys that have high electrical resistivity make ideal electric-heater materials. Their characteristic resistance to complete oxidation and retention of strength at high temperatures recommends them for use at red heat. Typical standard malleable heater materials are 80 per cent nickel, 20 per cent chromium (Nichrome IV) and 60 per cent nickel, 15 chromium, 25 iron (Nichrome). There are many variations, but all aim at higher resistivity, higher operating temperature, or both. Heavy cast resistors intended for high rates of heat dissipation are made from an alloy of approximately 20 per cent chromium, 35 to 70 per cent nickel, the remainder iron. The amount of nickel in the alloys is determined by the severity of the service. Alloys high in nickel will stand higher temperatures but are more expensive. Alloys with low thermal coefficients of resistance are used for precision electrical resistors. Constantan (45 nickel, 55 copper) and similar nickel-copper alloys have low thermal coeffi-

* Designations used by the International Nickel Co.

cients of resistance combined with fairly high resistivity (see Chapter 6).

The curie point for pure nickel is lowered from 780 F by the addition of alloying elements. The effect of various elements varies over a wide range, making possible formation of alloys with any chosen curie point from 780 to as low as −200 F. In binary alloys with 5 per cent of the alloying element, the curie point is depressed to increased amounts, in the order listed, by palladium, gold, platinum, copper, manganese, zinc, tin, antimony, molybdenum, titanium, chromium, aluminum, vanadium, and silicon. All the commercial alloys of nickel have a curie point below 0 F (at 1.05 permeability, from −92 to −200), except Monel, which has a curie point of about room temperature at 1.05 permeability.

8.28 ALLOYS WITH SPECIAL MECHANICAL PROPERTIES

Alloys containing 30 to 40 per cent nickel with iron are known as Invar, and are characterized by extremely small coefficients of thermal expansion. They are used in length standards, in measuring tapes, and for the low expansion element of bimetal thermostats. An alloy containing 36 per cent nickel has the lowest thermal expansion of the group and is used as a length standard by the International Bureau of Weights and Measures. An alloy with the same composition, except for the addition of 4 to 5 per cent chromium and 1 to 3 per cent tungsten, is Elinvar. It has a nearly constant modulus of elasticity with changing temperature, and is used principally for watch springs and precision instruments.

Pure nickel is also used in bimetal thermostats, but it is used as the high-expansion element of the pair. Many other nickel alloys are used in bimetals, because of their range of expansion coefficients and because of their moderately high operating temperatures.

Wire leads for glass vacuum tubes must have a special thermal expansion coefficient to match that of the glass, in order that a gas-tight seal may be maintained and that excessive stresses will not be set up within the glass during heating and cooling. The various kinds of glass have different coefficients of thermal expansion, and so different lead-in alloys are used. The common alloys of industry contain 13 to 48 per cent nickel, depending upon the expansion coefficient desired. Wonico, Kovar, Fernico, Fernichrome, and Platinite are trade names of alloys, in order of increasing nickel.

8.29 ALLOYS WITH HIGH MECHANICAL PROPERTIES AT HIGH TEMPERATURES

The importance of nickel as an alloying element or a base metal in nickel-chromium-iron alloys for mechanical uses involving high-temperature oxidation resistance or corrosion resistance has been covered in Chapters 5 and 7. The development of materials suited to gas turbines for jet propulsion, turbosuperchargers, etc., has resulted in a new group of alloys having high strength and creep resistance above 1200 F and up to 1500 F or higher. These alloys are known collectively as *superalloys*. They usually contain large amounts of chromium for oxidation resistance and large amounts of several other elements, such as molybdenum, cobalt, nickel, tungsten, columbium, and titanium. Although nickel is not the base metal in all these alloys, it participates in all, and so they are covered here for convenience.

Some superalloys for use at about 1200 F can be strengthened by cold working at 1200–1400 F. Those intended for use at higher temperatures are strengthened by precipitation-hardening heat treatment. The typical treatment consists in a solution anneal at 2300 F, water quench, and aging for 10 hr at 1400–1500 F.

Fabrication of these alloys is very difficult since they are designed to resist distortion even at relatively high temperatures. Forging is thus limited to small reductions at slow rates at temperatures of about 2300 F. Precision casting is used for fabricating many of the alloys. Shapes for cast parts are also limited for those materials which are strengthened by heat treatment.

These materials are new and under rapid development. The manufacturer should be consulted for latest alloys available and for property values of them. Typical properties of a few current alloys are given in Table 8.8.

Lead and Its Alloys

8.30 PROPERTIES AND USES OF LEAD

This metal occurs in at least 60 minerals but it is produced commercially almost entirely from galena, the sulfide of lead. The ore is concentrated by the flotation process, roasted to remove sulfur and agglomerate the particles, and then reduced with fluxes and coke in the blast furnace. The product of the blast furnace contains

Table 8.8 Typical Properties of Some Superalloys

Designation *	Short-Time Tensile Properties					Fatigue Strength 10^8 Cycles, M psi	
	Tensile strength, M psi			Yield strength 0 2% offset, M psi	Elongation in 2 in., %		
	70 F	1200 F	1500 F	70 F	70 F	1200 F	1500 F
Wrought Alloys 19-9DL	141 [1]	91		115	30	43 [4]	17 [4]
Timken, 16-25-6	162 [1]	107 5	.	143 5	15 5	46 [5]	19 [6]
K-42B	162 [1]	128	71	97	31	54 [4]	.
Inconel X	192 [1]	118	70	136	26	55	36
Nimonic	153 [1]	97.5		84	36	.	
Cast Alloys Vitallium (Stellite 21)— As cast 1350 F, 50 hr	101 3 .	74.2 89.3	59	82.3 .	8 2	44 .	33
X-40—As cast 1350 F, 50 hr	101 . .	77 .	59 59 6	74 .	11 . .	56	
6059—As cast 1350 F, 50 hr	82.5 . .	48.9 . .	51.2	46.9	7 . .	41	31
Hastelloy B	80-83.5 [1]	62.9-68.7	55.4-61.4	56.5-61.5	9.5-15	66 [2]	34 [5]

* Designations are from numerous manufacturers.

Table 8.8   Typical Properties of Some Superalloys (Continued)

Stress Rupture Strength, M psi—1000 hr			Creep Strength 1% In 10,000 Hr, M psi			Nominal Composition, %	Condition (see superscripts in associated data)
1200 F	1350 F	1500 F	1200 F	1350 F	1500 F		
50[3]	20.5[3]	10[5]	.	13[2]	6.5[2]	19 Cr, 9 Ni, 1 25 Mo, 1.2 W, bal. Fe	[1] Finish roll 1200 F, 1200 F stress relieved, 2100 F 1 hr, A.C [2] Hot rolled [3] Hot forged, 21% at 1200 F [4] 2100 F 1 hr, A.C., 15% C.W 1200 F, 4 hr at 1200 F [5] 2250 F, ½ hr, O Q., 50 hr at 1500 F
42[3]	19[3]	10[4]	20[2]		6 6[2]	25.2 Ni, 16.7 Cr, 6.25 Mo, 1 35 Mn, 0.7 Si, bal. Fe	[1] 2100 F, 1 hr, A.C, roll to 1200 F, S.R. at 1200 F, A.C. [2] 2150 F, W.Q. [3] 2100 F, A.C., 22.5% C.W. at 1200 F, S.R. at 1200 F [4] 50 hr S.R. at 1500 F [5] 2000 F, W Q., 4 hr at 1200 F [6] 2150 F, W.Q., 50 hr at 1500 F
39.5[2]	26.5[2]	15[3]	18.8	..	7 4	42 Ni, 18 Cr, 22 Co, 13 Fe, 2.5 Ti, 0.6 Al, 0.7 Mn, 0.35 Si, 0.06 C	[1] 1750 F, 2 hr, W.Q., 1200 F, 72 hr, F.C. [2] 1950 F, W.Q., 1350 F, 20 hr [3] 2100 F, W.Q., 1500 F, 20–50 hr [4] 2100 F, 1 hr, W.Q., 1350 F, 20 hr
55[3]	40[3]	18.5[4]	63[2]	37[2]	18[2]	70 Ni min, 14–16 Cr, 5–9 Fe, 0.7–1 2 Cb, 0.3–1 Mn, 0.4–1 Al, 2 Cu	[1] Hot rolled, aged [2] Normalized, age 24 hr 1550 F, 20 hr at 1300 F [3] 2100 F, 24 hr, A.C., 1300 F, 6–20 hr, A.C. [4] 2100 F, 4–24 hr, A.C., 1300 F, 6–20 hr, A.C.
45[1]	23.3[2]	11 8[3]	.		9.5	74.2 Ni, 21.2 Cr, 2.4 Ti, 0.63 Al, 0.6 Mn, 0 5 Si, 0.04 C, bal. Fe	[1] 1950 F, 2 hr, W.Q., 1300 F, 16 hr [2] 1950 F, 4 hr, W.Q., 1400 F, 50 hr [3] 1950 F, 4 hr, W.Q., 1500 F, 50 hr
43 ..	16	22 .	..	..	.	62.2 Co, 27.4 Cr, 5.5 Mo, 2.8 Ni, 0.7 Fe, 0 66 Mn, 0.53 Si, 0.22 C	
46 ..	34	23.2		..	13.7	55 Co, 25 Cr, 10 Ni, 7 W, 1 Fe, 0 7 Si, 0.6 Mn, 0.5 C	
46 ..	.. ..	18.4 ..	..	..	11.7 .	32 Ni, 23 Cr, 6 Mo, 0.6 Si, 0.6 Mn, 0.4 C, bal. Co	
33[2]	25[3]	11.3[4]	2.6	..	1.6	62.5/66.5 Ni, 26/30 Mo, 4–7 Fe, 0.6 Mn, 0.2 Si, 0.04–0.15 C	[1] As cast [2] 2000 F, 1 hr, W.Q., 1200 F, 4 hr, F.C. [3] 1950 F, 2 hr, A.C. [4] 1950 F, 24 hr, A.C. [5] 2050 F, A.C., 1900 F, 24 hr

silver, gold, and other impurities, which may be removed by the Parkes process, by electrolysis, or by the Betterton process. The Parkes process, which is most used, consists in melting the blast-furnace bullion, and cooling below the melting point of copper, which is then removed by skimming. The melt is then reheated and oxidized, causing antimony and arsenic to form a skin which can be removed by skimming. Molten zinc is then added to combine with gold and silver, and these constituents are then removed by skimming. The residue is commercially pure lead, often of 99.99 per cent purity.

Lead was one of the first, if not the first, metal used by man. Examples of it have been found in ornamentation dating to 3000 B.C. and the Romans made extensive use of it in water systems which have been in use for over 1900 years. It is still an important material to-day, with an annual usage in the United States of approximately 1 million tons. The quantity of lead used in the more important applications are listed in Table 8.9.

Table 8.9   Uses of Lead in the United States *

Application	Per Ce
Storage batteries	28.2
Cable covering	12
Tetraethyl for gasoline	7.8
Red lead and litharge	7.3
Building uses	6.4
White lead for paint	5.5
Ammunition	5.8
Bearing metal	3.8
Solder	3.8
Calking	2.9
Type metal	2.3
Foil	1.8
Terne plate	0.6
Miscellaneous	11.8

* Data for 1944 from *Metals Handbook*, 1948 edition; Am. Soc. Metals

The commercial grades of lead available are:

1. *Corroding lead,* which designates a high-purity lead, about 99.99 per cent pure, used by "corroders" in the manufacture of white lead for outdoor paint pigment.

2. *Chemical lead,* which designates the material from southeast Missouri containing 0.04 to 0.08 per cent copper. The copper improves the resistance to corrosion by certain chemicals and has led to use of this grade by the chemical industry.

3. *Acid lead,* which is made by adding 0.04 to 0.08 per cent copper to refined lead, forming a product similar to chemical lead, but having more bismuth and less silver.

4. *Copper lead,* another grade made by adding 0.04 to 0.08 per cent copper to refined lead somewhat less pure than for acid lead.

5. *Common desilverized lead,* which designates fully refined lead that is desilvered by the Parkes process. There are two grades, *A* and *B,* which differ in the amount of bismuth present. These grades are the usual ones for alloying with other metals.

6. *Soft undesilverized lead,* which designates lead mined in the Joplin, Missouri, district. It contains up to 0.04 copper and too little silver for desilverizing.

These grades may be rolled, drawn into pipe, impact extruded, die cast, or sand cast. The sheet lead is rolled in widths up to 11¾ ft with 8 ft the normal standard. Any desired thickness may be specified. The trade refers to thicknesses in lb/sq ft since 1 lb/sq ft is equivalent to $\frac{1}{64}$ in. in thickness. The sheet form is widely used in the chemical industry because of its resistance to sulfuric acid. Sheeting is also used for roofing material, for flashing, for shower pans, X-ray shields, and sound proofing. Lead pipe is excellent for transporting water and chemicals, and for plumbing traps. Foil is usually made by rolling a "sandwich" of lead between two sheets of tin. Total thicknesses of 0.0005 in. or less are common. Impact extrusions are used for collapsible tubes. Cast forms are used for storage batteries, toys, governors, and fire-extinguisher parts.

Alloys of lead with tin, antimony, and sometimes with copper, zinc, silver, alkali metals, bismuth or cadmium are used for solders (see Chapter 20), fusible alloys, bearing alloys (see later paragraph), type metals, and hard lead.

Fusible alloys have many uses. Typical of them are sprinkle system and boiler plugs, low-temperature baths, checking fixtures and aircraft forming dies, fillers for bending thin-wall tubing, mounting mediums for punches and parts, proof castings for dies and molds, and molds for wax-precision casting patterns. Typical compositions and melting points are given in Table 8.10. Some of those listed shrink upon solidification, others expand or show little volume change. Some contract and others expand during cooling to room temperature. Hardness of these alloys as a group ranges from 5 to 22 Bhn, tensile strength from 3000 to 13,000 psi, and elongation from 0 to 300 per cent. All creep at room temperature under relatively light loads.

Type metals are made in several grades, depending upon the sever-

Table 8.10   Typical Fusible Alloys

Melting Point or Range, F Eutectic Type	Pb	Bi	Sn	Cd	Others	
621	100					
478	82.5			17.5		
362	38.1		61.9			
291		60		40		
288	30.6		51.2	18.2		
255	44.5	55.5				
196.7	40.2	51.65		8.15		
158	26.7	50	13.3	10		
136	18	49.4	11.6		21	In
117	22.6	44.7	8.3	5.3	19.1	In
Noneutectic Type						
348–293	47.5	12.6	39.9			
343–266	50	20	30			
440–217	28.5	48	14.5		9	Sb
219–203	22	56	22			
194–158	37.7	42.5	11.3	8.5		

ity of press and handling operations. The customary grades, from softest to hardest, are electrotype, stereotype, linotype, monotype, and foundry type. Increased tin and antimony are used from about 3 per cent each for electrotype to 10–20 per cent tin and 20–28 per cent antimony for foundry type.

Hard lead designates antimony alloys with lead, often called *antimonial lead,* which range from 1 to 12 per cent antimony. The grades having 2–8 per cent Sb are hardenable by heat treatment, but the treatments are seldom used in practice. The 1 per cent alloy is used for sheathing for telephone and electric power cables. Chemical lead is usually employed sometimes with 0.03 Ca or up to 0.1 tellurium for higher creep and fatigue resistance. Alloys with up to 1 per cent arsenic and up to 2 per cent antimony are used for ammunition as shot or cores. Storage-battery castings contain about 6 per cent antimony and have excellent casting characteristics. For intricate castings, 0.25 per cent tin is often added for fluidity. Die-casting alloys contain 10 per cent antimony, or 15 per cent antimony and 5 per cent tin, with 0.5 copper. Other grades of hard lead are used for shrapnel and for collapsible tubes. See Table 8.11 for typical properties.

Table 8.11   Properties of Typical Lead Alloys *

Designation	Form	Tensile Strength, psi	Yield Strength, 0.5% Offset, psi	Elongation, %	Hardness, Rockwell, Special ½-in. Ball, 30 kg	Density, lb/cu in.
Commercial pure lead	Rolled sheet, longitudinal	2,500	1300	27 (8″)	75	0 41
	Extruded sheet, longitudinal	2,575		58 (2″)	78	0.41
Chemical lead	Sand cast	1,800	800	30	4 BHN	0 409
Antimonial lead (1% Sb)	Extruded, aged 1 month	3,000		50	7 BHN	0 406
Antimonial lead (8% Sb)	Rolled 95%	4,650		31 3	9 5 BHN	0 388
	235 C, Q, aged 1 day	12,350		4 7	26.3 BHN	0 388

* Approximate values of physical properties coefficient of thermal expansion, 27×10^{-6}/C, volume conductivity 7.5% of Cu as aged, specific heat, 0 033/C, cal/g at 68 212 F.

Tin

8.31   PROPERTIES AND USES OF TIN

Tin is the most important metal that is not mined commercially in North America. Peacetime production of virgin tin has ranged from 10,700 to 170,000 short tons per year from 1931 to 1940. The United States consumption has varied from 35 to 55 per cent during that period. The metal is obtained from its mineral oxide, cassiterite, from mines in the East, Bolivia, and Central Africa. Deposits are of the vein or lode type in Bolivia and usually of the placer type in the other commercially worked locations. Since both types are mined and concentrated at the site, the ore for refining contains 18 to 65 per cent tin. The ore is reduced with carbon in reverberatory furnaces or blast furnaces. Ordinary purity grade is obtained by liquidation, and high-purity grade is obtained electrolytically or by chemical processes.

Uses for tin are many and are probably more widespread than for any other metal. It is used in pure form in rolled foil, extruded collapsible tubes and pipes, and as powder for use in metallizing, decorative paper, and solder pastes. Metallic coatings are applied by chemical deposition on decorative parts, by electrodeposition on iron, by hot dipping on iron, copper, brass, and lead, and by metallizing. Alloy uses include solders, "white-metal" bearings, phosphor bronze, type metals, die castings, and pewter. It is also used in chemical compounds ranging from organic lubricating oils and pharmaceuticals to inorganic tin oxide for porcelain enamel and tin chloride for tex-

tile dying and bleaching. The relative quantities of tin used in peacetime applications are shown in Table 8.12 which is an average for

Table 8.12   Uses of Tin in the United States *

Application	Per Cent
Tin plate and terne plate	50.2
Solder	15.7
Brass and bronze	7.3
Babbitt and white metal	7.9
Collapsible tubes	5.1
Tinning (other than tin plate)	3.6
Foil	3.5
Galvanizing	1.3
Pipe and tubing	1.2
Tin oxide	1.0
Miscellaneous	3.2

* From Bureau of Mines, average for 1939 to 1941.

1939 to 1941. The two largest uses, plating and soldering, are described in Chapters 22 and 20 respectively. With the exception of bearing metals, tin-base alloys are not widely used for other product applications. Two alloys of most importance are pewter, an alloy with up to 20 per cent lead, and britannia metal, an alloy with antimony. Both are used for decorative tableware. The latter, with 7 per cent antimony and 2 per cent copper, is more popular for rolled ware because of greater stability, tarnish resistance, and strength. Die-casting compositions contain 4.5 per cent each of antimony and copper, or larger amounts of antimony, up to 15 per cent, with equal or less copper.

The short-time tensile strength of pure tin ranges from 2100 psi to 3100 with 96 to 55 per cent elongation. All forms suffer creep at room temperature under stresses as low as 160 psi. Other properties are modulus of elasticity 6 to 6.5 million psi, modulus of rigidity 2.4 million psi, Poisson's ratio 0.33, volume conductivity 15 per cent of copper, melting point 449.4 F, transformation white (beta) to alpha (gray), 55.8 F, specific heat, $0.0534/C + 0.0000348t$ from 0 to 100 C, and density (β) 0.2637 lb/cu in. at 59 F. Transformation of beta or white tin to the less-dense gray, or alpha, form causes disintegration in the form of powdering or local "warts." Although the transformation has an equilibrium temperature of 55.8 F, a considerable undercooling is required to start it. It proceeds rapidly at −40 F, but is very difficult to initiate. Presence of bismuth (0.1 per cent), lead

(1–2 per cent), and antimony assure that the change will not occur under any likely conditions of exposure. Gold, silver, and nickel also inhibit the action. Aluminum, magnesium, zinc, and cobalt accelerate the transformation and should be avoided in pure tin subject to low temperatures.

Bearing Metals

Since many of the nonferrous metals are used as base metals for bearing alloys, the discussion of these typical alloys and their applications is grouped in this section.

8.32 BEARING REQUIREMENTS

Bearings are machine elements designed to transmit loads or reaction forces from a movable member to the bearing support. Although sliding ways, bridge-expansion plates, and other devices involving linear motion are properly classed as bearings, this discussion is directed mainly to cylindrical (full or segmental) and ring-shaped (full or segmental) members used respectively for journal and thrust bearings with rotatable shafts. There are a large variety of such bearings which operate under different pressures, types of loading, temperature, corrosive influences, method of lubrication, sliding velocity, and with different shaft materials. Because of the range of design and service conditions involved, no metal is suited to all applications. Materials for each bearing application must be selected as the best compromise for the design and service condition present. Selections are best made with benefit of actual service experience, but the use of simulated laboratory tests is growing. The more important characteristics of bearing materials that must be considered are briefly reviewed in the following paragraphs.

Loading. The magnitude of the load and its nature are perhaps most important. Heavy loads require high compressive strength to avoid deformation, brinelling, or extrusion of bearing metal under use or shipment, and ductility to absorb pounding and avoid flaking or cracking. When the bearing length is increased to reduce unit loading, alignment of the shaft may become poor. A low modulus of elasticity and plastic deformability are then needed to avoid high unit pressure at extremes of the bearing. When the load is intermittent or alternating, fatigue strength of the bearing material may become limiting. Design of the bearing, including rigidity of the supporting structure, thickness of backing material, and degree of bond

between bearing material and support, all affect the fatigue resistance of the bearing metal.

Temperature. A number of factors influence the maximum temperature the bearing material must resist. The surface speed of the shaft, the rate of lubricant supply, the possibility that lubricant supply will fail for short periods, the conductivity of the bearing material, and the frequency of starting and stopping are typical. They all relate to the amount of heat generated and the rate the heat is dissipated. The maximum temperature encountered must be resisted by the bearing material without excessive loss in strength and without promotion of excessive corrosion.

Corrosion. Corrosion is influenced by factors other than temperature. The presence of water, contaminating atmospheres, the lubricant itself, the inhibitors used, any change in the lubricant with service (e.g., acid formation), the permanency of lubricant supply, and the metal combinations involved in the shaft and the bearing are typical (see Chapter 5).

Abrading and Seizing. Most journal and thrust bearings are designed to run on a continuous oil film. Bearing clearance, method of lubricant supply (grooves, rings, waste or wick, grease cups, etc.), and sealing methods are design considerations affecting continuity of the oil supply. When the risk of lubricant failure is high, materials must be chosen for good resistance to scoring or actual seizing. Even with the best lubricant supply, metal-to-metal contact of bearing and shaft will be caused by stopping, starting, high deflection of components, sudden shock loads, or overloads. If the speed is low enough, the heat generated by the metal-to-metal contact can be dissipated rapidly enough to avoid scoring. As speeds become higher, the heat cannot be carried away rapidly enough, and temperatures reach the point where scoring occurs, with actual seizure under extreme conditions. Because of this characteristic, higher shaft hardness is required for aluminum-base, copper-base, and cadmium-base bearings than for the babbitts. "Oiliness," that is, the ability of the oil to wet the bearing surface, tends to reduce scoring, but corrosion conditions that will decrease oiliness with use offset the advantage of this property.

Bearings in sealed refrigerant systems are well protected from contaminating dirt if cleanliness is exercised in assembly. However, bearings for railroad trucks and farm machinery are examples where exposure to dirt is uncontrollable. The dirt may enter the bearing clearances and must either cut a groove around the bearing

and shaft, or be embedded into the bearing material. The babbitt materials are well suited when dirt conditions are uncontrollable. If copper, bronze, or aluminum bearings must be used, hardening of steel shafts is desired to avoid wear at low speed or overheating at high speed from foreign dust and metal particles (see also Wear, Chapter 4).

Structure. It was formerly believed that the best bearings consisted of two phases having hard crystals embedded in a soft matrix. The hard particles were purported to contact the shaft with minimum friction, and the soft matrix was thought to distort and conform to the shaft. Experiments have shown that solid-solution alloys of the matrix materials have equivalent bearing characteristics up to the limit of their load-carrying abilities. The effective purpose of alloying, which results in two phases, is now believed to be the increase in strength achieved. A second effect is the tendency of alloy elements, such as uncombined lead, to smear across the surface, thus offering the antiseizing effect of such materials with the basic strength of its alloy backing. Iron and graphite, alloys with lead, bismuth, or cadmium, bearings coated (usually electroplated) with tin, cadmium, silver, and copper, and the newer single-phase alloy bearings are other examples that support this viewpoint.

Ordinarily, the crystal size produced with conventional casting practice is not significant in bearing performance. Exceptions may be babbitt materials produced under very slow cooling, where the large crystals will reduce fatigue strength and may cause mottling of the surface during use.

8.33 BABBITT ALLOYS

These alloys derive their name from Isaac Babbitt, who developed a tin-base bearing alloy containing antimony and copper in 1839. Originally, this alloy was the only "babbitt." Subsequently, the term has been extended to all white-metal bearing alloys, whether of lead, tin, cadmium, or zinc base. These materials have hard constituents in a soft matrix. The crystals of the hard constituent should be controlled so as to be large enough for the matrix to distort, and small enough to avoid scoring of shafts. In general, these bearings have excellent antiseize characteristics, can be used at high sliding velocity under light load, and are supported by a steel or bronze bearing shell to improve their load-carrying capacity. In the past, unbonded or poorly-bonded babbitt liners were

cast in thicknesses that would permit machine finishing to $\frac{1}{8}$ or $\frac{1}{4}$ in. Many are still gravity cast or centrifugally cast and then machined. The current practice is to bond all babbitts to the backing (for steel 0.040 to 0.120 in.) and to reduce the liner thickness to about $\frac{1}{64}$ in. Some applications at 0.002 in. have been successful, and platings of 0.001 in. on stronger intermediate layers look promising. The original practice was to cast babbitt bearings in place and machine to finish. Automobile practice now involves use of cast steel-babbitt bimetal sheet which is rolled, blanked, formed, and broached as half bearings. Another technique being used is sintering of copper nickel to steel, casting the babbitt into the pores, and then the bearing is finished by blanking, forming, and broaching.

Lead-Base Alloys. Lead-babbitt alloys are of two types: (*a*) alloys with tin, antimony, and sometimes arsenic; and (*b*) alloys with calcium, tin, and alkaline earth metals. Alloys of type (*a*) have been known for many years, but importance of arsenic additions has been recognized only since about 1940. In the absence of arsenic, the alloys consist of cubic antimony-tin crystals or antimony in a matrix of lead-antimony-antimony tin. Antimony content above 15 per cent results in excessive brittleness for bearing application. The arsenic additions develop fine, uniform structure, and increase the mechanical properties at elevated temperatures. The 1 per cent arsenic alloy is widely used in automobile practice; the 3 per cent alloy in diesel engines. Copper to 0.5 per cent is sometimes added to prevent antimony-tin segregations. The tendency toward thinner babbitt liners has resulted in improved fatigue characteristics and lead-base babbitts of 0.030 in. are at least equivalent to tin base. Still thinner sections to 0.005 in. are superior. Type (*b*) alloys are used almost exclusively in the railway field and for diesel engines. Small amounts of tin and calcium with minute amounts of other elements result in hardness comparable with the higher tin-base alloys, but most of the type (*b*) compositions are subject to corrosion by acidic oils.

Tin-Base Alloys. Tin babbitts are composed of tin alloyed with 2–10 per cent antimony and copper and with as much as 30 per cent lead to limit cost. Zinc and arsenic are limited because they impart too much resistance to deformation. Aluminum modifies the microstructure and bismuth forms a low melting point eutectic, so these elements, too, are limited in these babbitts. Although lead is added to the low-tin alloys, it is limited to 0.35 per cent when

tin is above 75 per cent because of a Pb-Sn eutectic which melts at 361 F. Compared to other bearing materials, tin-base babbitts have relatively low resistance to fatigue but they are suited to low-load situations. They are easy to bond, easy to handle, have excellent antiseizure qualities, low friction, low coefficient of expansion, have good embedability and comformability, and resist corrosion better than lead-base alloys. They are generally employed for more severe service than lead-base babbitts when thick sections are used.

Cadmium-Base Alloys. These babbitts are superior to lead and tin-base babbitts in fatigue strength and temperature resistance. The cadmium is hardened with up to 3 per cent nickel or with less than 1 per cent silver and copper. Their cost is high, because of the availability of cadmium, and so they have been used mainly in aircraft applications. Some difficulty is experienced in bonding them to steel, with scoring unless shaft hardness is 250 Brinell or higher, and with their corrosion resistance to lubricant acids. Indium plating diffused into the bearing (heating 340 F for 2 hr) has improved corrosion resistance in this respect.

Zinc-Base Alloys. Zinc bearings are often employed as part of die-cast bearing housings. An alloy of 85 per cent zinc, 10 per cent copper, and 5 per cent aluminum has been successfully used under low, steady loading at high speeds. It has a low coefficient of friction but becomes brittle and is likely to seize at elevated temperatures.

8.34 COPPER-BASE BEARING ALLOYS

Copper Lead. This type of bearing material is widely used in the aircraft and automotive fields. Present practice is to cast the alloy in steel strip and to blank, form, and broach the bearing. The alloys most used are 67–74 copper, 25–32 lead, 1.5 max silver, and 60–70 copper, 30–40 lead. High lead contents lower fatigue strength and friction. Additions of silver to 5 per cent, and a plated overlay of lead tin over 25 per cent lead bearings are developments which appear to have higher fatigue properties. These alloys are easily corroded by certain lubricating oils, and diffusion of plated indium is often used to improve their corrosion resistance. Steel shafts used with these bearings should be of 300 Brinell or higher.

Bronzes. Several types of bronze are used for bearing applications. They are tin bronze, leaded-tin bronze, and aluminum bronze. Tin bronze bearings are made with 5 to 20 per cent tin, and phos-

phorus is limited to 1.0 per cent. When zinc is used instead of phosphorus, 2–6 per cent zinc may be retained. The phosphorus type is chosen for high load capacity at low speed, whereas the zinc type is preferred for intricate castings for foundry control at some sacrifice in strength and improved ductility. Lead is added to the tin bronzes for wrist pins and other bushings. The percentage lead usually increases with tin, and ranges from 4 per cent to 25 per cent in various grades. In general, little difference in wear properties is noted for alloys with 15–25 per cent lead and 4–7 per cent tin in locomotive and journal bearings. Aluminum bronzes containing 8–11 per cent aluminum and 3–7 per cent iron are used for heavy duty wearing surfaces but require very low speeds if lubrication is poor. These alloys, too, should be used with steel over 300 Brinell in hardness.

8.35 OTHER BEARING MATERIALS

Silver Bearings. These bearings are made by electroplating silver on a steel shell that has been coated with a flash of copper. The electrodeposit is annealed, machined, and then a 0.0004 to 0.001 in. coating of lead having 5 per cent indium or tin for corrosion resistance is added. These bearings can support heavy loads, and their high thermal conductivity lessens liability of seizure from local high spots.

Aluminum-Base Bearings. Three aluminum alloys have been used to some extent as bearings. They are: (1) 7 per cent tin plus small amounts of nickel and copper; (2) 7 per cent tin with $2\frac{1}{2}$ per cent silicon; and (3) 4 per cent each of cadmium and silicon. They are all two-phase alloys and are used solid or with steel backing. The latter seem to have higher fatigue resistance and are less affected by the high coefficient of expansion of aluminum. These bearings are used with steel over 300 Brinell in hardness and appear superior to babbitt and copper-base bearings but inferior to silver for heavy-load applications.

Powder Bearings. Bearings of copper alloys, iron, etc., made by powder metallurgy are often used for medium duty in small-size bushings. They may be impregnated with lubricant, which is advantageous in many designs (see Chapter 16).

Antifriction. Ball, roller, and needle bearings are used for low friction, precise alignment, very high speeds, and high loading. The load is supported by metal-to-metal contact, and failures occur usually by fatigue. High-strength steels are therefore used for balls,

rollers, and races. SAE 52100 is customarily employed for both members at a hardness of 60 to 62 Rockwell C. Carburized AISI 4620 and 8720 are sometimes employed. When extreme corrosion resistance is needed, SAE 518100 steel is often used at a hardness of 56–60 Rockwell C. For nonmagnetic applications, as in aircraft compasses, K-Monel and beryllium-copper races and ball bearings have been developed.

Zinc

8.36 CHARACTERISTICS AND REFINING

Zinc is a fairly heavy, bluish-white metal used principally because of its low cost, corrosion resistance, and alloy properties. Its density is slightly less than that of copper, but it costs only about half as much.

The principal zinc ore is the sulfide zinc blende. The ore is concentrated by flotation, after which it is roasted in the presence of air to yield zinc oxide. The oxide may be reduced either in a furnace or electrolytically. In furnace reduction, a mixture of zinc oxide and coal is fired, the zinc is vaporized, reduced at high temperature, and then caught and liquefied in a condenser. The purity of the zinc produced varies with the type of ore but is usually not less than 98 per cent. Zinc of 99.99 + per cent (special high grade) purity may be produced in large quantities by fractional distillation of the less pure zinc.

The electrolytic reduction of zinc is begun by dissolving the oxide in sulfuric acid. The resulting zinc sulfate solution is used as the electrolyte. The purity of the zinc produced depends upon the purity of the electrolyte; if the electrolyte has been chemically purified, zinc of 99.99 + per cent can be produced by this method also.

The strength of zinc is not great, and static loads well below the ultimate strength will cause creep even at room temperature. The temperature range through which zinc and its alloys retain their strength is relatively narrow. The upper limit is the recrystallization temperature, 100 to 115 C, above which they have very little strength. The lower limit for many parts is a freezing temperature, below which zinc alloys are brittle. If a part must stand shock at low temperatures, it should not be made of zinc.

In the less pure grades of zinc, the most common impurities are lead, tin, and cadmium. Their general effect is to harden the zinc and reduce its ductility and corrosion resistance. The quantity and kind of impurities present determine the exact properties and cost. There are characterstic uses for each of the several grades of zinc, which range from 98 to 99.99 per cent purity.

8.37 USES

Table 8.13 shows the relative quantity of zinc used for various industrial applications in 1946.

Table 8.13 Uses for Zinc in the United States *

Application	Per Cent
Galvanizing	40.2
Die castings	26.0
Brass making	18.7
Rolled zinc	11.7
Other purposes	3.4

* From American Bureau of Metal Statistics, 1946.

Zinc Coatings. The protection of iron and steel from corrosion is done more often with zinc than with any other metal coating. The oldest and most important methods of applying the zinc coating are known as *galvanizing.* This is done either by dipping the iron in molten zinc or by electroplating. Hot-dip galvanizing is done largely with the less pure grades of zinc, although high-grade zinc is often used for wire coatings that must stand bending without flaking. The zinc for electrogalvanizing may be obtained either from zinc anodes or by direct solution from the ore and subsequent purification in the electrolyte. The life of the galvanized material is proportional to the thickness of the coating. In order to achieve good adhesion, however, the surface of the iron must be carefully acid dipped and scrubbed before galvanizing.

When the part to be coated cannot conveniently be galvanized, a zinc coating may be sprayed on the surface. Small parts may also be coated with a very uniform zinc surface layer by a process called Sherardizing.

Die Casting. Zinc alloys have been widely used in die casting because their over-all cost is low. The casting temperatures are moderate, and plastic inserts, metal inserts, or insulated wire can be cast into the part. The pressures available in zinc die-casting machines are moderately high, and the castings can be made with

good density, relatively little porosity, good dimensional accuracy, and in very thin sections.

Table 8.14 Typical Properties of Zinc Alloys

	Tensile Strength, M psi	Compressive Strength, M psi	Elongation, %	Hardness, Brinell, 500/10	Shear Strength, M psi	End. Limit, M psi 10^8 Cycles	Remarks
Zamak 3 (¼"), die cast	41	60	10	82	31	6.87	
Zamak 5 (¼"), die cast	47.6	87	7	91	38	7	
Rolled zinc hot rolled							
longitudinal	21		52	43		3.8	(0.05–0.10 Pb,
transverse	25		30	..		..	0.05–0.08 Cd)
Rolled zinc alloy hot rolled							
longitudinal	28		20	61		6.8	(0.85–1.25 Cu,
transverse	36		10	..		..	0.006–0.016 Mg,
cold rolled							0.15 max Pb,
longitudinal	37		20	..		..	0.04 Cd)
transverse	48		2	..		..	

Volume conductivity: 26–28% copper.
Density: 0.24 to 0.258 lb/cu in. at 70 F.
Specific heat: 0.10 cal/gm/C at 68–212 F.

Alloys containing zinc of low purity cannot be used in die castings since they decompose by intergranular corrosion, especially in warm, humid atmospheres. This is because aluminum, which is used in all die-casting alloys, combines with any lead, tin, or cadmium that may be present and forms unstable phases. All the alloys recommended for die casting are therefore made from special high-purity zinc. The alloy, as cast, is limited to minute percentages of the impurities lead, cadmium, and tin. Two alloys, known as Zamak-3 and Zamak-5, are in common use. They contain 3.5–4.3 per cent aluminum, 0.03 to 0.8 magnesium, and max of 0.007 lead, 0.005 tin, 0.005 cadmium, 0.10 iron, and remainder high-purity zinc. The Zamak-5 alloy also contains 0.75 to 1.25 per cent copper.

After casting, there is a shrinkage of the order of 0.001 in. per in., which takes place over a period of weeks but which can be immediately brought on by annealing. After this is done, the dimensions of the die-cast part are very stable, unless the casting alloy is high in copper. Parts containing 2.5 per cent copper may be expected to expand 0.001 in. per in. during a period of 5 yr, but those with lower copper content have better dimensional stability.

Brass Making. All the grades of zinc may be used in brass making, but the purity is of considerable importance in determining the physical properties. Brasses made wth 10 to 36 per cent zinc were formerly hot short and very difficult to hot work. Today, however, special high-purity zinc makes it feasible to hot work these brasses, but zinc of lower purity is still frequently used in brass making.

Wrought Forms. The wrought zinc of industry varies considerably in purity, and usually contains up to 1 per cent added copper. It is ductile and easily formed at room temperatures. Many articles, such as dry battery cans, eyelets, and vanity cases are drawn from rolled zinc sheet or strip. Although cold working hardens the metal, the effect of cold work is lost at only moderately elevated temperatures. During the time zinc retains the effects of cold work it may have as much as double the strength along the direction of the distorted grains as across them.

8.38 MACHINING AND FINISHING

Most zinc parts are not machined, since die castings or wrought parts are formed directly in their final shape. When machining is necessary, it is easily done, especially if the tools are correctly ground.

Wrought zinc can usually be soldered with soft solder. The die-casting alloys, however, are difficult to solder because of the coat of aluminum oxide. If die castings require soldering, it should be done to an insert of copper or brass in the casting, or the part should be nickel-plated.

Zinc alloys are plated or painted for decoration as well as protection. The surface preparation is of greatest importance in obtaining an adherent coat. Some finishes are baked on, but temperatures above 250 F (recrystallization temperature) are seldom used.

Other Nonferrous Metals of Commercial Importance *

Antimony. Ths metal is usually found combined in the trisulfide from which it is obtained by direct reduction with iron. Antimony is relatively hard and much too brittle for use in pure form. It

* See Chapter 1 for physical constants of these metals.

is used mainly as an alloying constituent in type metal, fusible alloys, bearing metal, and as a hardener for lead.

Beryllium. The only important source of beryllium is the mineral aluminum-silicate called beryl. About 300 tons of beryl containing 3 to 4 per cent of beryllium are produced domestically each year. Imports normally run 3 to 4 times this amount. The metal is extracted commercially by electrolysis of the oxyfluoride.

A good part of the ore is used for manufacture of beryllium oxide, which is an excellent refractory. It resists corrosion, cracking, and thermal shock and melts at 4660 F. Other beryllium compounds are sometimes used in fluorescent lights.

The pure metal is used as alpha-ray emitters and as a moderator for chain-reaction atomic piles. Since the metal is 17 times as transparent to X-rays as aluminum, it is often used in 0.001- to 0.002-in. thick windows for X-ray tubes. Beryllium has a specific gravity of 1.8, a modulus of elasticity of 42 million psi. It is worked with difficulty; rolling, swaging, or extrusion must be performed at 750 C under suitable protection. Room-temperature tensile strength is 40–50,000 psi, with 2 per cent elongation.

The largest use for beryllium is an as alloying element with copper (2–2.5 per cent Be), forming precipitation-hardening alloys that approach steel in hardness and strength. These alloys are non-magnetic, nonsparking, have good electrical conductivity, and show excellent resistance to shock, wear, and fatigue. Cobalt additions replacing the beryllium (e.g., 2.6 per cent Co, 0.5 per cent Be, bal Cu) form alloys having high heat resistance and good conductivity for contact springs. Heat-treatable alloys of interest are also formed with some aluminum alloys and with iron chromium nickel, but all are limited mainly by the low availability of beryllium and its cost.

Bismuth. Bismuth is produced mainly as a by-product in the refining of copper, lead, or zinc. It occurs combined as the oxide or, more usually, the sulfide. Refining is accomplished by roasting to obtain the oxide and reducing with carbon. The pure metal is soft, very brittle, and of low thermal conductivity. It is used mainly for solders and fusible alloys. Woods metal (a 4 parts Bi, 2 Pb, 1 Sn, 1 Cd alloy) melts at 60.5 C and is widely used for steam safety plugs and automatic sprinkler systems. The bismuth-lead eutectic does not change volume upon solidification at 254 F and is used for pattern duplication. A bismuth-tin-lead-antimony alloy, known as matrix alloy, pours in the range 480–600 F and is

nonshrinking. It is used for short-run dies, as a mounting medium for complex dies, and for die repair. Some high-bismuth alloys are used for seals between glass and copper or brass.

Boron. This metal occurs in nature combined as a nonmetal in sodium and calcium compounds. Some 10 to 20 tons are marketed each year as ferroalloys containing 10 to 19 per cent boron or as 15–20 per cent alloys with manganese or nickel. Such boron alloy additions to medium-alloy steels appreciably increase the hardenability and replace a disproportionately larger amount of molybdenum (see Chapter 7). Next to the diamond, boron nitride and boron carbide are the hardest materials known and are used for sand-blast nozzles. Nickel and chromium alloys with boron are used for hard surfacng and for cutting tools.

Cadmium. Cadmium is usually obtained as an impurity in zinc ores and is extracted by distillation. Its principal use is as a galvanic protective plating on small steel articles. It is also widely used in low-melting alloys for solders, silver-brazing alloys, and fusible plugs. It is used to 1 per cent with copper as a hardener for trolley wires, and with silver or nickel in cadmium-base bearings which will withstand higher temperatures than tin- or lead-base bearings.

Calcium. Production of calcium by electrolysis is difficult because of rapid oxidation and high hygroscopy of the salt. Aluminothermic reduction in a vacuum has been successfully performed. The metal is employed as a deoxidizer for copper, and for reducing oxides of such metals as chromium, titanium, uranium, and zirconium. The silicon and silicon-manganese alloys are excellent decarburizers and desulfurizers. Calcium additions to lead are used in cable sheathing and in some bearing alloys (see also Chapter 13).

Cerium. Cerium is one of the "rare-earth" metals that occur together in certain minerals. It can be separated only by laborious fractional crystallization or precipitation. Electrolysis produces mischmetal, an alloy of several rare-earth metals. Both produce brilliant sparks and are used in lighter flints, tracer bullets, and ignition devices. Pure cerium is also used in high-temperature magnesium alloys and nichrome electrical-resistance wire.

Chromium. The most important chromium ore is the ferrous chromite. Ferrochrome, a 1–8 per cent chromium alloy with iron, is used for adding chromium to steel, and it is obtained by direct reduction of the ore with carbon. The pure metal is obtained from the oxide by reduction with aluminum. The most important use

of the pure metal is in electroplating. Thin coatings are used for their lustrous appearance and thick coatings for wear resistance (see Chapter 22). Alloy applications are equally important, because chromium is a constituent in low-alloy steels, stainless steels, cutting steels, heat-resisting steels (see Chapter 7), and electrical-resistance alloys (see Chapter 6). It is also used in a number of superalloys for high-temperature service.

Cobalt. This metal usually occurs with nickel in arsenic ores and is obtained by reduction with aluminum. Properties of cobalt are similar to nickel, but its magnetic properties are second only to iron. Cobalt is used in steel alloys for cutting tools, and dies (see Chapter 7), in iron permanent-magnet alloys (see Chapter 6), and as a base metal in superalloys for very high-temperature service.

Columbium. The chief ore of columbium is the iron columbate that is refined by aluminothermic reduction, by reduction with coal, or by electrolysis of fluorides. The ferrocolumbium containing 50–60 per cent columbium is used for adding the metal to stainless steel, where it serves to combine with carbon and stabilize the steel against intergranular corrosion. It is also used to promote grain growth and reduce embrittlement of nitriding alloy steels and as a constituent in some superalloys.

Gallium. Minute quantities of gallium are obtained from sulfuric acid plant flue dust, from the residue of zinc distillation, or from rare minerals. The pure metal is noted for its low melting point, 85 F, and its high boiling point, 4170 F. The long liquid range is utilized in high-temperature quartz thermometers. It also has excellent corrosion resistance and forms exceedingly white mirrors on glass.

Germanium. Germanium is produced as a by-product of cadmium and zinc refining, and is extracted by hydrogen reduction of the purified oxide. The pure metal is a semiconductor which has a nonmetallic crystalline structure similar to the diamond. Its largest application is for crystal detectors and rectifiers for microwave electronic applications. A potential field of application lies in its silver and gold alloys, which expand upon solidification and have low melting points. Such properties are useful in dental and jewelry parts and in solders. Other potential applications may employ its ability to alloy with platinum, iron, copper, and the light metals; the very high index of refraction of its glass; and its very high electrical resistance.

Gold. Gold is the most ductile and malleable of all metals and is usually found in the pure state mixed with gravel or as veins in other rocks. The pure material is separated by panning and sluicing, which depend on the high density (sp gr 19.3), or by amalgamation with mercury and later extraction by volatization of the latter. Vein deposits are crushed and the gold separated either by amalgamation or a cyanide process. The latter is best suited to small particles. It consists of treatment with a soluble cyanide solution, forming a soluble complex gold cyanide, separation of the solution, and reducing the gold by precipitation with another metal. Silver may be present in appreciable quantities and it is usually separated by electrolysis.

Besides the use of gold as a money standard and for coinage, it is widely employed for jewelry, dental work, decorative purposes (as gold leaf), and as electroplated coatings. Its value has often obscured its high resistance to all chemicals, except the halides, which has resulted in many applications to chemical processing equipment.

Indium. This metal looks like silver and tin, but is soft and ductile like lead. It is obtained as a by-product of zinc and lead production. The principal use of indium is in lead or cadmium bearings. The indium is electroplated over the lead or cadmium and the coating is diffused with the surface, where it promotes oil retention and reduces wear. Other uses are: a plating over silver to reduce tarnishing; an 18 per cent alloy with woods metal to obtain a 117 F melting solder; alloying with lead and tin for solder to resist alkaline corrosion; a solder for glass and metal useful over a narrow temperature range; and as a neutron indicator in the atomic pile.

Iridium. Iridium is one of the hardest, most brittle, most corrosion resistant, and most difficult to work of all the metals. It is used mainly in platinum alloys as a hardener for jewelry and electrical contacts, and as insoluble electroplating anodes. The 10.1 per cent iridium alloy is used for standard lengths and weights because of its low rate of thermal expansion and excellent resistance to atmospheric corrosion. Alloys with osmium are used for fountain-pen tips.

Lithium. Electrolysis of the chloride is the usual method of producing lithium, the lightest of all metals. Its applications are generally limited by its high reactivity with water and oxygen. The latter property is used for reacting with free gas in vacuum tubes

(as a "getter"), for protective furnace atmospheres, and for deoxidizing copper. Lithium is also used as a minor constituent in lead, copper, aluminum, and magnesium alloys.

Typical compounds of lithium employed in industry are: (1) its hydrides and peroxides as sources of H_2 and O_2; (2) the aluminum hydride as a reducing agent; (3) its soaps, which are used in glass, ceramics, and lubricants; (4) and others which are employed in detergents, storage-battery electrolytes, and welding fluxes.

Manganese. The most important source of manganese is the ore containing its dioxide. The pure form is obtained by the Goldschmidt process (reduction with aluminum at high temperature), but iron alloys for addition to ferrous metals are obtained by reduction with carbon in the blast furnace.

Pure manganese is hard and brittle and the metal is used almost entirely as an alloying element. It is added to steels either as the ferromanganese alloy having up to 80 per cent Mn or as Spiegeleisen having up to 20 per cent Mn and some carbon. The latter is used as a deoxidizer and to add carbon after the Bessemer process. The manganese scavenges sulfur in steels (also nickel alloys), increases strength of low-alloy steels, and provides abrasion resistance in austenitic steels containing 10–14 per cent Mn. Manganese additions are also made to aluminum and magnesium for imparting hardness and strength without loss in corrosion resistance, and to silicon bronzes and high-strength brasses. A manganese-copper-nickel (10 Mn, 80 Cu, 10 Ni) alloy, called manganin, is used for standard electrical resistances because of its low temperature coefficient of resistance. Another alloy with 72 per cent Mn, 18 per cent Cu, and 10 per cent Ni has a very high coefficient of expansion and is used for thermostatic bimetals.

Mercury. Although mercury is sometimes found free in nature, the most important source is the sulfide from which it is extracted by heating and distillation (melting point 624 F).

Pure mercury is the only metal which is a liquid at room temperatures. This property and its high density are employed in barometers, thermometers, and other scientific instruments, and as a confining seal for vacuum pumps. The electrical conductivity of the liquid and the gas is employed in small tilt-type electric switches, in mercury-vapor lamps, and in mercury arc rectifiers. Properties of the gas are employed in diffusion (vacuum) pumps and in high-temperature "topping" turbines.

Molybdenum. The commercial source of this metal is its sulfide, from which it is purified by successive reduction with oxygen and then hydrogen. In industry it is marketed in many forms, such as ore concentrates, alloys, molybdates, and oxides.

The pure metal is ductile and has a high modulus of elasticity and high strength. It oxidizes rapidly at fairly low temperatures, and coating with ceramic materials, titanium, and alloys through electrodeposition and thermal decomposition are under study for high-temperature uses.

Molybdenum is a very important hardener for steel. It raises grain-coarsening temperatures, increases hardenability, minimizes temper brittleness, and imparts high-temperature creep strength. It is equally effective in cast irons. Its alloys with nickel have excellent heat and corrosion resistance for chemical equipment. Typical applications of molybdenum alloys are to jet engines, incandescent-lamp supports, electric contacts, heating elements, welding electrodes, and X-ray targets.

Osmium. This is the heaviest of all metals (sp gr 22.48), which melts at 4900 F and is harder than glass and quartz. It is not worked successfully either hot or cold, but can be sintered at 3600 F. The principal uses are for hard corrosion-resistant alloys, for pen and phonograph-needle tips, and for specially hard electrical contacts.

Palladium. This metal resembles platinum but is harder, stronger, lighter, and is attacked by concentrated nitric acid. It is very ductile and can be drastically cold worked. It is used in clad form for chemical apparatus and for electric contacts for light contact pressures as in telephone relays.

Platinum. Platinum is a silver-white heavy metal, unaffected by acids, air, or a great variety of chemical agents. It is attacked by chlorine and aqua regia. It is extensively used, either solid or clad, for chemical equipment. Other uses are for chemical catalysts, dentistry, electrical contacts, electrical-resistance furnace heaters, and jewelry.

Rhenium. Rhenium has been produced in limited quantities from molybdenum smelter flue dust. The metal looks like silver, has a density exceeding gold, has extremely good corrosion resistance, and a melting point of 3170 C, exceeded only by tungsten. It forms hard acid-resistant alloys with tungsten, molybdenum, chromium, and tantalum. Because of its high melting point it shows promise

for high-temperature thermocouples, lamp filaments, electric contacts, and similar uses as its availability increases.

Rhodium. This metal also looks like silver, and it can be worked at room and elevated temperatures. It is harder than silver and resists attack by chemical and industrial fumes. Platings of the metal accurately reproduce the subsurface. Uses include plating of searchlight reflectors, and alloys for electric contacts, rayon spinnerets, resistance-furnace heaters, and thermocouples.

Rutherium. Another of the platinum group, this metal is hard to work but can be forged at 2700 F. The main application is as an alloying element to harden and increase corrosion resistance of platinum and palladium.

Selenium. This metal is produced from the residue of electrolytic copper refining. Its metallic form is gray with a specific gravity of 4.81 and a melting point of 428 F. Selenium cells employing its characteristic change in electrical conductivity upon exposure to visible light are its most common application. They are used in counters, scanning and sorting machines, safety devices, and light-meters. The metal is also used in electric rectifiers and for decolorizing glass. Its principal alloying application is in copper alloys where 0.5–0.6 per cent adds to machinability. Similar characteristics are imparted by adding 0.25 per cent to invar and stainless steel.

Silicon. This is the most abundant metal in the earth's crust. It occurs in oxides of common rock and quartz and in silicates. The oxide is the usual source and it is reduced with carbon at electric-furnace temperatures. Ferrosilicon for addition to steel is prepared by adding iron oxide to the furnace charge.

Although the metal has excellent resistance to acids (except HF) and to atmospheric corrosion, its use has been limited by its brittleness and poor formability. The ferrosilicon has been added to steels to form electrical core sheets (see Chapter 6), and as a deoxidizer for steel. Silicon additions are also made to brasses, bronzes, aluminum, and magnesium alloys.

Silver. The use of silver in industry has expanded very rapidly during the last few years. For many centuries silver was used for ornament and for coinage, and remained a relatively scarce metal. Since about 1900, however, modern mining methods and the production of silver as a by-product in mining other metals have brought a very large quantity of silver to the market. Although the price is

still high, nevertheless industrial uses in the United States account for about one-fourth of the world's supply.

The high conductivity and excellent corrosion resistance of silver are good reasons for its use in electrical contacts (see Chapter 6). Alloys of silver have been used in soldering and brazing because of their high strength and corrosion resistance (see Chapter 21). Silver has even been added to heavy-duty bearing metals, with improvements in strength and resistance to vibration.

Sodium. This metal is made on a large scale by electrolysis o sodium chloride. Most of the production goes into the manufacture of chemicals. Metallurgical uses are relatively minor but include hardening of lead-bearing alloys, removal of arsenic and antimony from lead-tin alloys, deoxidation of metal baths, and descaling of steel. The pure metal is being used as a coolant and heat-transfer medium from 400–800 C in aircraft engines. Experiments are under way to utilize its electrical conductivity, which is 3 times that of copper on a weight basis.

Tantalum. The chief ore of tantalum is the mixed tantalate and columbate of iron and manganese. Pure tantalum is prepared by fused-salt electrolysis or by reduction of its halides with lithium or sodium. Because of its tendency to form nitrides and carbides, it is prepared by powder-metallurgy methods and sintered in a vacuum. Cold-working methods may be employed for fabrication. Uses of the pure metal include surgical sutures and plates, chemical apparatus, electronic anodes and grids, rectifiers, condensers, and lightning arresters. Its carbide is used for cutting tools, dies, and parts of extraordinary hardness and wear resistance. It also alloys with tungsten for higher mechanical strength and higher annealing temperature.

Tellurium. This metal, like selenium, is obtained from the residue of electrolytic copper refining. It is practically a nonconductor of electricity and has no light-sensitive properties. Industrial uses are as a minute alloying element to increase work hardenability and recrystallization temperature of lead and tin, increasing the chill of iron, and improving the machining properties of copper alloys and stainless steel.

Thallium. All domestic production of thallium is from cadmium flue dust. The metal is malleable, soft, and has a low melting point. It tarnishes rapidly upon exposure to air, but is added to lead to improve corrosion resistance. A thallium-lead alloy is used in electric fuses. Many of its uses are nonmetallic in such items as fungicides,

insecticides, and rat poison. Its glasses have high refractive index, and its addition to selenium cells improves sensitivity. It is also added to mercury-vapor rectifiers and lamps.

Thorium. Thorium is a gray-white metal that is of low mechanical strength, ductile, soft, and easily cold worked. It is used in photo-electric cells, X-ray targets, and glow-tube electrodes. Small additions are used to restrict grain growth and prolong high-temperature life of nickel-chrome and platinum resistors. Its oxide is used to restrict grain growth in tungsten filaments and for highest-melting-point furnace linings. The metal forms a radioactive series like uranium but of shorter life than radium.

Titanium. This metal is the most promising newcomer to the structural field. It is the fifth most abundant metal, and is light, strong, and corrosion resistant. Despite its abundance, the cost of titanium has been high because of the technical difficulty of refining and fabricating it. The present refining method consists in reducing the tetrachloride with magnesium under a protective helium gas, and then leaching the magnesium chloride and free magnesium with cold hydrochloric acid. The resulting powder or sponge of 99.5 per cent pure titanium is then melted above 3272 F in vacuum or inert atmosphere crucibles which are cooled to chill the titanium and form, in effect, a solid titanium mold. The high affinity for oxygen in all known refractories, and for carbon, nitrogen, and hydrogen, prevents use of conventional melting methods. Research is underway to develop less expensive refining methods since the powder produced by pilot plants in 100-lb lots costs 5 dollars per lb.

The density of titanium lies between aluminum and steel (sp gr 4.5), the strength compares with heat treated steels, and the thermal conductivity and corrosion resistance compare well with chrome-nickel stainless steel. Although titanium is very active chemically at high temperature, it resists oxygen and moist air well to 600 F. The metal protects itself with a tightly adhering oxide which affords this protection and also resists many caustic and acid solutions as well as salt water. The good strength and light weight affords a higher strength-weight ratio than steels or light metals up to 800 F. Titanium is serviceable to 1000 F, but its strength-weight ratio is inferior to steel above 800 F.

Fabrication of titanium appears very promising. Forging and rotary swaging are successfully performed at 1600 to 1800 F. Higher temperatures result in excessive gas absorption, and lower ones are accompanied by harder working and retained cold work. Strip, wire,

and rod may be produced cold with reductions up to 50 per cent. Rolling of this magnitude typically raises the tensile strength from 90,000 to 135,000 psi and reduces elongation from 30 to 10 per cent. Welding processes that may be employed include spot, seam, inert-arc, and oxyhydrogen cutting. For the resistance methods the titanium must be clean and free of scale, but room-temperature oxides that form after cleaning are not harmful. In the welds there is a tendency for brittleness in the area adjacent to the weld.

Properties of commercially pure titanium are approximately as follows: yield strength 60,000 psi annealed to 110,000 psi hard rolled, tensile strength similarly 75,000 to 140,000 psi, and elongation 25 to 10 per cent; stress rupture strength at 750 F is 35,000 psi for 1000 hr; specific heat, 0.13 Btu/lb F; coefficient of thermal expansion, 5×10^{-6}/F; electrical conductivity, 3.2 per cent IACS; and thermal conductivity 105 Btu/ft^2 F hr/in. Alloys are under rapid development. Typical of those available are several in the ranges 1.8 to 3 per cent Cr, 0.9 to 1.5 per cent Fe, and 0.15 to 0.5 per cent C, with ultimate strength 125 to 175,000 psi, yield strength 80 to 160,000 psi, and elongation of 20 to 10 per cent. The 7 per cent Mn alloy has 150,000 psi tensile, 140,000 psi yield strength, and 12–15 per cent elongation, with 75,000 psi endurance limit. Properties of the 4 per cent Mn and 4 per cent Al alloy are about equivalent. A 5 per cent Cr, 3 per cent Al, and 0.4 per cent C alloy has 165,000 psi tensile, 135,000 psi yield, and 10 per cent elongation.

Currently, titanium is used for some castings and forgings for air-craft, an alloying element to stabilize carbides in stainless steel, pre-cipitation-hardenable copper alloys, and high-strength nickel cobalt iron. Its carbide is mixed with others for cutting tools, and other minerals are used for dye salts and pigments, smoke screen materials, and weld rod coatings. Titanium will wet glass and some ceramics giving promise of forming a solder for joining these materials to other metals for very high temperature service. —

Tungsten. The principal commercial sources of tungsten are the minerals in which it is combined with calcium, iron, or manganese, from which the pure metal is obtained by reduction of the oxide with hydrogen. It is compacted, sintered in a hydrogen atmosphere, and worked at successively lower temperatures until it becomes ductile. It has unique properties. The melting point is the highest of all elements (6115 F), the density is equal to gold, its vapor pressure is very low, its modulus of elasticity very high (53 million psi), and

its conductivity is relatively good. These properties give the metal its unique position for lamp filaments.

Other uses include alloy steels, high-speed tool steels, hot-working tool steels, and steels for strength at high temperature (see Chapter 7). It is also used in nonferrous alloys, such as stellite, electrical contacts, hard-surfacing welding electrodes, spark plugs, radar grids, counterweights, and with other carbides in carbide cutting tools.

Vanadium. Pure vanadium is a ductile metal that may be drawn into wire but metal of the necessary purity is not produced commercially. More than 90 per cent of the production is of ferrovanadium, which is added to high-speed tool steels, and as a carbide-forming element for steels to be used at elevated temperatures. It is also added to gray cast iron to improve strength and hardness, and to alloyed irons to improve machinability. More limited use has been made of vanadium in highly magnetic noncobalt alloys, in some bronzes, and in Hastelloy. About 3 per cent of the metal produced is used as a catalyst, replacing platinum in chemical processes.

Zirconium. The main source of this metal is the silicate zircon, used as a precious stone. As zirconium ferrosilicon, it is relatively inexpensive, and in this form it is added to steel as a deoxidizer and grain-refining agent. It is an excellent scavenger for oxygen, nitrogen, and sulfur. The addition to high-quality low-alloy steels is practiced where highest ductility for wrought material is desired. Its high boiling point and affinity for O_2 and N_2 have resulted in use of the pure metal as a getter for vacuum tubes. It is also used for flashbulbs and pyrotechnics. Its superior corrosion resistance to acids and alkalis, its ductility, and work hardenability suggest further application in alloys.

About half the production of zirconium goes into vitreous enamels, porcelains, and glass (see Chapter 13). Another 30 per cent is utilized for zirconia, zirconium oxide, refractories that have a very high melting point and excellent chemical, mechanical, and electrical properties.

8.39 CONCLUSION

The foregoing discussion of each of the nonferrous metals has been intended as a general summary of the facts important in designing to use each of these metals. When a material must be selected, this general information should narrow the field to a group of metals or alloys that meet the requirements. To determine the one metal or alloy which is best, however, may often require a knowledge

of facts that have not been presented here. The physical properties of the hundreds of nonferrous alloys may best be obtained from design handbooks or from manufacturers' specifications. The designer should also determine the current cost of the material, as well as the fabricating cost, and compare these with the costs for other metals.

Review Questions

1. How do copper, aluminum, magnesium, zinc, and their alloys compare with plain low-carbon steel in (a) magnetic properties, (b) melting point, (c) electrical and thermal conductivity, (d) tensile strength, (e) modulus of elasticity, and (f) base cost of metal?

2. (a) Aluminum naturally has good corrosion resistance. To what characteristic of the metal is this due? (b) How does "anodization" increase the corrosion resistance? (c) Do soldered alumium joints have good resistance to corrosion?

3. A pound of alloy steel will support a tensile load as great as can be supported by a pound of aluminum alloy, and, in addition, the steel occupies less space. Yet aluminum is often used in aircraft. Give at least two reasons for its use.

4. (a) In general, how do the compositions of aluminum-casting alloys differ from those of the alloys for wrought forms? (b) What are the two principal alloying elements used with aluminum, and why is each used?

5. (a) Name the three grades of commercial copper and tell how they differ in composition. (b) Where strength is important, which would be used for a cold-drawn wire that is to be soldered? for a part to be gas welded?

6. (a) Which brasses are best adapted to cold working and which to hot working? (b) Under what conditions can cartridge brass (30 Zn) be both hot and cold worked successfully?

7. Brass is subject to two characteristic kinds of corrosion. Name these and the types of brass most susceptible to each.

8. (a) What special precaution should be observed in designing magnesium castings? (b) What special practices must be used in the foundry?

9. Many nickel alloys have been developed, each to satisfy at least one specific requirement. Name at least four of these requirements.

10. Give two advantages and two disadvantages of zinc-alloy die castings.

9 NONMETALLIC MATERIALS

by M. M. SPRUNG *

9.1 INTRODUCTION

Until about 1910 chemical science was concerned largely with the composition and structure of naturally occurring materials, and with increasing and perfecting their usefulness. It seemed little likely, at that time, that physical and chemical knowledge would be so much enlarged, and techniques so rapidly developed in the next few decades, that useful manmade materials would challenge those found in nature in number, in versatility, and in complexity. This is, however, a major task to which chemical science has since then been particularly devoted. Historically, the process has had two major goals: first, to understand the principles through which important naturally occurring substances are built; and second, to apply and extend these principles in the laboratory and in the factory to prepare new products. The effects set in motion by early studies have, in truth, carried far beyond the dreams of those who pioneered in these investigations. Nature is versatile as well as bountiful. However, profound structural changes occur in nature only at great intervals. New forms of matter, or modifications of old forms, are not discovered frequently, nor when most wanted. In the test tube or in the reaction kettle additions and alterations in reactants and in conditions can be made almost at will. It is not surprising that the term "tailor-made molecules" has come to be more than a mere catchword or advertising slogan. With literally thousands of raw materials to combine, rearrange, modify, and blend, the total possible number of distinctive end products indeed staggers the imagination.

In the present chapter, therefore, the major coverage will be devoted to a description of important types of synthetic nonmetallic materials and to the general principles governing their structures and properties. Those natural products which are still of great

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industrial importance, or which serve to illustrate principles of constitution or synthesis, will also be considered in their proper relationship to analogous or cognate synthetic substances.

9.2 CLASSIFICATION

Any classification of nonmetallic materials must necessarily be somewhat arbitrary. One conventional and useful classification recognizes a division into "inorganic" and "organic" types, with subdivisions into materials of natural and synthetic origin. Within such a loose framework most of the common nonmetallic materials can be disposed as follows:

Classification of Nonmetallic Materials

1. *Inorganic*
    (a) Natural
        Stone
        Minerals and ores
        Clays and loamy deposits
        Salts
    (b) Synthetic
        Cement
        Concrete
        Plaster and gypsum
        Glass
        Ceramics
            Brick
            Porcelain
            Vitreous enamels
        Fused silica and alumina
        Graphite
        Carbides, etc.
2. *Organic*
    (a) Natural
        Components of natural gas
        Components of petroleum
        Components of carbonaceous deposits
        Simple carbohydrates
        Wood
        Cellulosic products other than wood
        Shellac
        Leather
        Cork
        Natural rubber
        Natural resins
        Natural fibers

(*b*) Synthetic or Modified
   Paper
   Regenerated cellulose
   Cellulose derivatives
   Artificial leather
   Synthetic resins
   Synthetic rubbers (elastomers)
   Synthetic fibers.

9.3   RELATIONSHIP WITH METALS

The chemistry, physics, and mechanics of metals are highly complex subjects, as is clear from preceding chapters. But most metallic systems can be defined in terms of a number of rather precisely related and measurable properties. For example most metallic systems have (*a*) a definite melting point, (*b*) a limited number of transition temperatures, attributable to definable changes in structure, (*c*) measurable and reproducible mechanical properties, such as tensile strength, thermal expansion, modulus of elasticity, and yield strength, and (*d*) characteristic crystalline pattern under normal conditions. Frequently, nonmetallic materials also conform to these relationships. In the field of plastics, for example, a specialized technology is devoted to mechanico-elastic (i.e., metal-like) behavior.

Because of the great diversity and multiformity of nonmetallic materials, however, gross departures from these and similar quantitative relationships are often encountered. This can be illustrated by a rather extreme, but not uncommon, example. A block of pure quartz and a specimen of "bouncing silicone putty" both contain silicon and oxygen atoms bound to one another in intimate, specific relationship. Otherwise, they show little or no similarity. The quartz is representative of an ordered, crystalline solid; the putty is as strikingly a physically disordered, amorphous structure.

Types of Chemical Bonding   _

Matter may be viewed as held together by three fundamental types of bonds: (*a*) ionic or heteropolar; (*b*) covalent or homopolar; and (*c*) secondary valence or cohesive.* Metals occupy an intermediate position, as will be shown presently.

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* This classification, a convenient and enormously useful one, is yet essentially qualitative and arbitrary. In the rigid mathematical expressions of quantum mechanics, no real discontinuity between these types of binding forces is recognized.

9.4   IONIC OR HETEROPOLAR BONDING FORCES

In the ultimate view, any substance is composed of atomic nuclei and electrons held together in such an arrangement that the potential energy of the system is a minimum.   Particularly in the case of many inorganic compounds, the atoms, or certain closely associated atomic groupings, are ionized in the solid.   This ionization consists in the giving up of one or more electrons by one atom or group and their acceptance by another.   These atoms or groups therefore perma-
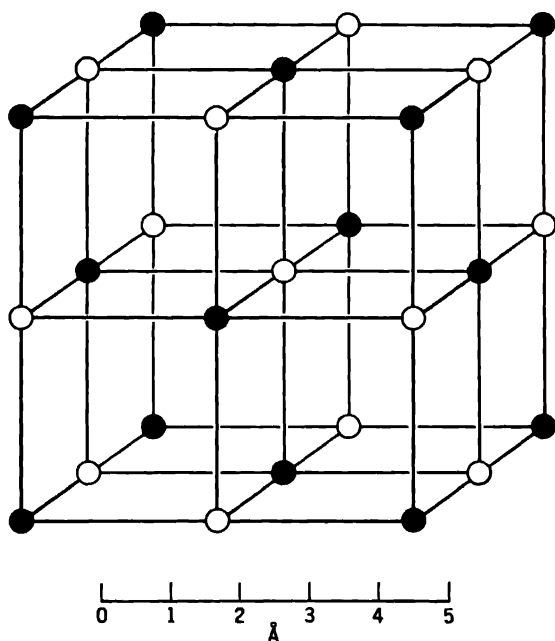
Fig. 9.1.   The crystal structure of rock salt (NaCl).   One type of circle represents Na$^+$ ions, the other Cl$^-$ ions.   The distance between like atomic centers along any principal axis is 5.63 A (5.63 $\times$ 10^{-8} cm).   (*From Atomic Structure of Minerals, by W. L. Bragg, Cornell University Press, Ithaca, New York, 2nd printing, 1950.*)

nently carry either positive or negative charges.   In this structural sense there is no *a priori* reason to expect discontinuities or boundaries in a solid so composed of spatially arranged ions, except through imperfections.   A "perfect" crystal of this type would contain a regular and indefinitely extensive arrangement of negatively and positively charged centers.   The electrostatic bonds formed between the ions of opposite polarity are understandably called "heteropolar" bonds.

In this view, for example, a crystal of pure rock salt contains only ionic bonds. A regular arrangement of positive sodium ions (Na^+) and negative chlorine ions (Cl^-) exists in the crystal. The molecular weight of such a substance is a purely fictitious concept. No individual atom or ion bears a unique relationship to any second atom or ion. Through the regularity of spatial arrangements, a given ion will in general bear an identical relationship to each of several neighboring ions; and each of these, in turn, will bear an identical relationship to several of its neighbors. Thus, the entire crystal may be viewed as constituting a single, giant molecule of indeterminate molecular size and weight. An inspection of the sodium chloride crystal model (Fig. 9.1) will make this fact more apparent.

9.5   COVALENT OR HOMOPOLAR BONDING FORCES

In contrast to this situation, a symmetrical gas, ideally in its normal state and at infinite dilution, presents a good example of *covalent* bonding forces. As with an ionic crystal, bonds are formed by the special disposition of valence electrons; i.e., by the few electrons which are particularly available for chemical bonding because of their location (ordinarily) in the outermost of the several concentric groupings of electrons, called "shells," surrounding each elementary nucleus. (See the chart, Fig. 9.2, of the periodic classification of the elements for some details.) With covalent compounds, however, complete transfer of electrons from one atom to another does not occur. Instead, a process of "sharing" is visualized. Sharing involves the joint or coordinated action of electrons derived from the valence shells of each of the atoms involved. In the quantum mechanical sense, the resulting electronic orbitals involve contributions (not necessarily equal) from each of the atoms concerned. In another sense, the valence electrons simply act in pairs to form the covalent bond. Since complete electrostatic displacements do not occur, the bond is also said to be *homopolar;* i.e., it does not involve the attractions of centers of opposite polarity.*

Under idealized conditions the valence electrons of the homopolar bond may be considered to be equally shared by the paired atoms forming the bond; for example, in a simple diatomic † gas such as

* For the sake of simplicity, the modern concepts of resonance and hyperconjugation are ignored in the present treatment.

† "Diatomic" = 2 atoms per molecule. Except for the rare gases of the atmosphere (argon, neon, etc.) which are monatomic, all elemental gases are diatomic in their normal states (e.g., hydrogen, oxygen, nitrogen, chlorine, etc.).

nitrogen, Fig. 9.3a, or even in a more complex organic vapor such as the hydrocarbon, ethane, Fig. 9.3b. The crosses and dots represent, schematically, valence electrons originally "belonging to" one or the

F I G. 9.2. Periodic Arrangement of the Chemical Elements. Above the name of each element is its atomic number; below, its chemical symbol and atomic weight. Since the publication of this table in 1948, two new artificial trans-uranium metals have been announced; Berkelium (No. 97) and Californium (No. 98).

other of the paired atoms. In the nitrogen gas each of the atoms originally had 5 electrons in its outermost shell. On combining to form the nitrogen molecule, 3 valence electrons from each atom are shared. In ethane 8 atoms are involved—2 carbon and 6 hydrogen. Each carbon originally had 4 valence electrons and each hydrogen had 1. In the molecule there are 6 covalent C—H bonds formed by

the sharing of all the valence electrons of hydrogen with carbon, and 1 covalent C—C bond formed by sharing of the last available valence electrons of the carbon atoms with one another.

$$: N \overset{x}{\underset{x}{}} \overset{x}{\underset{x}{}} N \overset{x}{}$$

(a)

$$\begin{array}{cc} H & H \\ \cdot\,x & \cdot\,x \\ H \overset{x}{:} C \overset{x}{:} C \overset{x}{:} H \\ \cdot\,x & \cdot\,x \\ H & H \end{array}$$

(b)
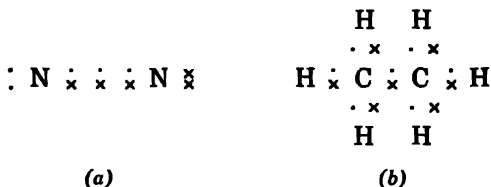
Fɪɢ. 9.3. (a) Nitrogen gas. N denotes nitrogen atom. (b) Ethane. C denotes carbon atom. H denotes hydrogen atom. Crosses and dots denote valence electrons originally "belonging to" one or the other of the paired atoms.

The molecular weight, in such cases, is exactly defined as the sum of the atomic weights concerned, and is readily determined by measurement of vapor density, to which it bears an exact proportionality.

9.6 SECONDARY VALENCE OR COHESIVE BONDING FORCES

It is necessary to elaborate somewhat on the nature of secondary valence forces before proceeding further. Three sources of attraction between neutral molecules are commonly recognized. They are: (1) the permanent dipoles * that exist in most nonsymmetrical molecules and owe their origin to separation of electrical charges; (2) the polarization induced in neighboring molecules by these permanent dipoles; and (3) the electric interactions of rapidly shifting charge distributions in the molecule. The last of these are the only important sources of intermolecular attraction in simple symmetrical molecules, and are of greatest importance in most other cases. The name of van der Waals, who pioneered in examination of forces of attraction between neutral molecules, is almost universally associated with them.

The distinction between primary and secondary valence forces is a vital one, and must be appreciated clearly before gross chemical and physical properties can be understood. Primary valence forces (which may be either homopolar or heteropolar, as previously described) cause atoms to *combine* with one another to give stable molecules. Complete mutual saturation of force fields, however, never results from such combinations. Otherwise, molecules would exert no attractions upon one another, and would eventually fly apart

* The nature and consequences of dipole attraction will be discussed at greater length in the section on electrical properties, Sec. 9.29.

into ultimate space. It is the secondary valence forces which exert attractions *between* molecules. In a liquid or in a homopolar solid these forces are van der Waals. In a broad sense they are the forces of attraction associated with residual force fields remaining after atoms combine through primary valence forces into more or less stable molecules.

In a gas, such as methane, for example, the van der Waals forces are weak. They cannot prevent ceaseless motion of gas molecules—motion occasioned by the kinetic energy of the gas. However, in solid methane, the kinetic energy of translation is almost, if not entirely, overcome. The van der Waals forces now are able to hold the molecules in a stable crystalline pattern. Thus, in solid methane, both primary, covalent forces and van der Waals forces are clearly definable.

Crystals, such as those of solid methane, are called *molecular crystals*. Molecules occupy the lattice points. The intermolecular binding forces in molecular crystals may be van der Waals or they may be dipole orientation forces. In the rare gases, in diatomic elements, in carbon dioxide (CO_2) in carbon monoxide (CO), in the hydrogen halides, HCl, HBr, and HI (but not HF), in methane, and many other organic compounds the crystal lattice forces are entirely or nearly entirely van der Waals. Dipole orientation forces are more important in water, in hydrogen fluoride (HF), in methanol (CH_3OH) and similar alcohols, in hydrogen peroxide (H_2O_2), etc. These and many other *polar* molecules attract one another more strongly than can be accounted for by van der Waals forces alone.

9.7 METALLIC BONDING FORCES

As suggested above, the metallic bond may be considered as a special, transitional type, bearing some relationship both to the spatial ionic bond and to the nonspatial covalent bond. The outstanding property of metals lies in the high degree of mobility of certain of the component electrons. Thus, in a typical metal, such as copper, the valence electrons are able to shift rapidly between preferred positions in the lattice. In another sense a metal consists of positive ions which are held together, not by fixed negative ions, but by rapidly shifting electrons.

9.8 CRYSTALLINE AND AMORPHOUS SOLIDS

Crystalline solids possess order and symmetry and usually show well-defined boundary conditions. In general, crystalline solids obey

Hooke's law; i.e., deformation under an applied stress is proportional
to the stress, and reversible within relatively wide limits. A liquid,
in contrast, has no elements of external symmetry and cannot remain
at equilibrium under a shearing force. Many solids behave as though
intermediate in structure between liquids and truly crystalline solids.
Such solids are termed *amorphous,* a term which unfortunately must
be used to cover a very wide range of behavior and of types. The
molecules in completely amorphous solids are arranged at random.
Definite physical boundaries cannot be recognized. Conchoidal
(shell-like) fracture is one common evidence of this condition. On
X-ray analysis, completely amorphous solids yield indefinite pat-
terns, similar in some respects to those of liquids, again suggesting a
lack of internal organization. Many materials of great usefulness
in industry and art are amorphous. Some important examples are
discussed below.

To illustrate the structural complexities with which one must some-
times be concerned, consider a naturally occurring organic substance
of very considerable molecular weight, such as native cellulose.
Known facts concerning the structure of cellulose may be summarized
somewhat as follows: The molecules consist of very long chains of
carbon, hydrogen, and oxygen atoms, held together by covalent, pri-
mary valence bonds. A complex mixture of chains of varying lengths
is always present; but to each individual chain can theoretically be
assigned a definite molecular weight related to its chain length, and
equal to the sum of the weights of all the atoms in the chain. The
individual chains are somewhat randomly oriented, but in an approxi-
mate sense they are roughly parallel to one another in a direction re-
ferred to as "the fiber axis." Between such oriented chains, rela-
tively strong cohesion forces (secondary valence forces) operate,
holding the molecules into bundles sometimes termed *micells.* X-ray
examination has disclosed a definite crystalline pattern for the cellu-
lose fiber that is built up from these imperfectly oriented chains. A
schematic diagram of the unit cell * of cellulose is shown in Fig. 9.4.
This fiber by no means has the properties of a single crystal, such
as those which can be obtained from metals, for example. It is rather
a partially crystalline aggregate containing small crystal areas
(crystallites) separated by amorphous areas. These relations are
shown schematically in Fig. 9.5. This highly complex state of affairs
is typical of many organic substances, both natural and synthetic.

* A definition of this term is given in the section that follows immediately.
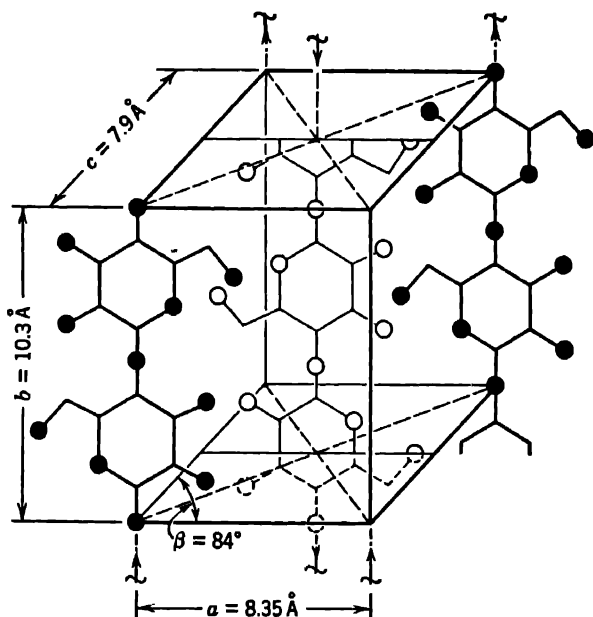
FIG. 9.4. The unit cell of native cellulose, according to Meyer and Misch. The circles represent oxygen atoms; the points where lines running from the oxygens join or change direction represent carbon atoms. Hydrogen atoms are not shown. (*From X-Ray Examination, by W. A. Sisson, in Cellulose and Cellulose Derivatives, E. Ott, ed. Copyright 1943, Interscience Publishers, New York.*)
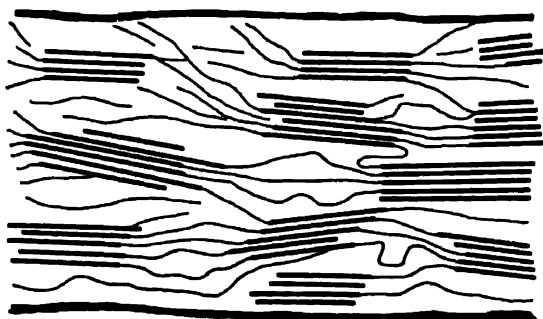
FIG. 9.5. Schematic representation of the gross structure of cellulose. The heavy, approximately parallel lines are crystalline areas (crystallites). The fine, wavy lines represent unoriented chains, which, taken together, constitute amorphous areas. Individual molecular chains may begin, end, or run through the crystallites. (*By permission, from Colloid Chemistry, Vol. 6, by Jerome Alexander, Reinhold Publishing Corp., New York.*)

Structure of Inorganic Materials

9.9 MINERALS

The crystalline nature of many minerals was recognized as early as the eighteenth century. Crystallography, although now treated as a separate science, has developed in parallel with scientific mineralogy. Most minerals can be fitted into a formal crystallographic system. For example, quartz (which may be nearly pure silicon dioxide, SiO_2) crystallizes in the rhombohedral system, generally as six-sided prisms, sometimes terminated by six-sided pyramids. Galena, lead sulfide (PbS), occurs in the isometric system, usually cubic in form, but truncations sometimes give octahedral, dodecahedral, or even trisoctahedral forms.

One of the most important problems in the study of a mineral specimen is to establish the crystallographic system to which it belongs. The disposition or arrangement of points in a crystal at which the pattern repeats itself is called a *space lattice*. Within a space enclosed by these points a complete unit of pattern is found, and this is called the *unit cell*. In all, there are fourteen special kinds of space lattices, which constitute the fourteen crystallographic systems. These are shown in Fig. 9.6.

The composition of a mineral is usually determined by ordinary methods of chemical analysis. A few important examples: igneous rocks, frequently used in construction, consist principally of the oxides of silicon and aluminum, with lesser inclusions of iron, calcium, magnesium, etc.; slates, which are geologically derived from clayey sediments, are very similar to these aluminum silicates in gross chemical composition; sandstones are composed essentially of grains of quartz, cemented together by iron oxides, lime, or clay; limestones are basically calcium carbonate $(CaCO_3)$; and granites contain quartz, feldspar (largely potassium aluminum silicate), mica, and sometimes hornblende (a complex calcium, iron, aluminum, magnesium silicate). Most minerals are understandably hard, durable, impervious, and stable towards heat, light, and moisture.

The silicate minerals display almost every conceivable variety of crystallographic complexity. But in almost all known silicate rocks, the silicon atoms are surrounded by four oxygen atoms at nearly ideal tetrahedral angles, and the silicon-oxygen bond distance is fixed at about 1.6 A $(1.6 \times 10^{-8}$ cm). Often, regular ring structures are found in the crystal. Sometimes there are zigzag chains of alternate
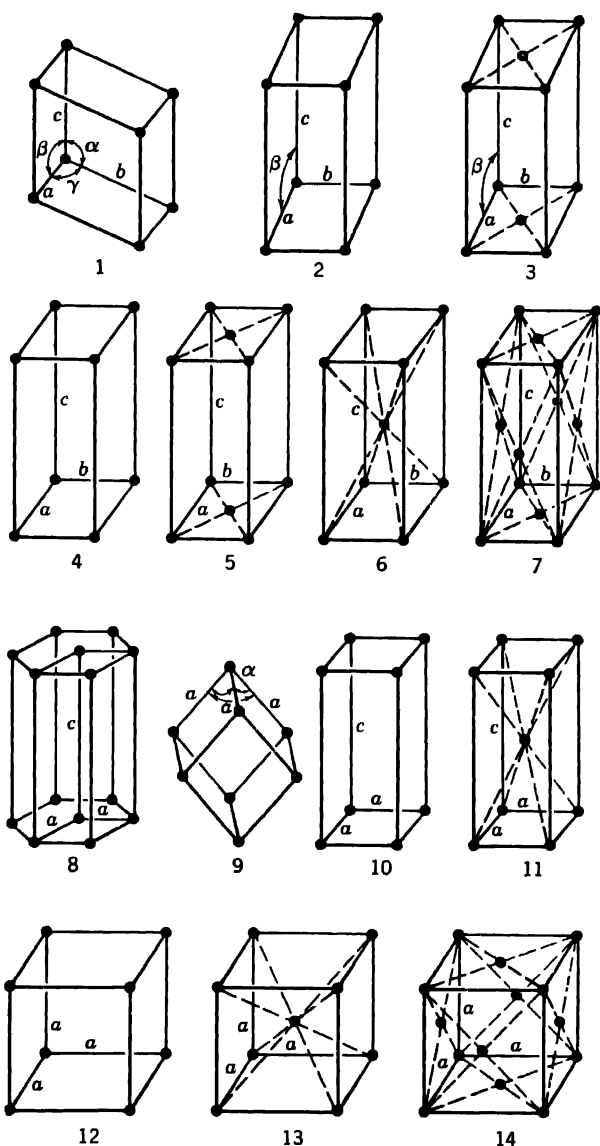
FIG. 9.6. The fourteen crystallographic systems: (1) triclinic, this model has the lowest elements of symmetry; (2) simple monoclinic; (3) a-face centered monoclinic; (4) simple orthorhombic; (5) a-face centered orthorhombic; (6) body-centered orthorhombic; (7) face-centered orthorhombic; (8) hexagonal; (9) rhombohedral; (10) simple tetragonal; (11) body-centered tetragonal; (12) simple cubic; (13) body-centered cubic; (14) face-centered cubic. (*By permission, from Atomic Structure of Minerals, by W. L. Bragg, Cornell University Press, Ithaca, New York, 2nd printing, 1950.*)

Si and O atoms. Three-dimensional silicon-oxygen networks occur in quartz and in some related minerals.

Mica is a mineral of special interest, particularly to the electrical industry. The platelike structure makes it possible for mica to be used where some flexibility is required. The crude mineral can be split into sheets which may have a thickness as low as 0.0005 in. It has unusually high thermal stability and under some conditions may be used up to 500 C. In continuous segments it has a very high dielectric "strength" and very low dielectric loss factor.* Chemically, micas are complex silicates of magnesium, aluminum, iron, and potassium. Muscovite corresponds to $KAl_2(AlSi_3O_{10})(OH)_2$; phlogopite to $KMg_3(AlSi_3O_{10})(OH)_2$. Crystallographically, it is possible to detect a succession of thin double sheets in mica, with the potassium atoms located between them. A model of a mica crystal is shown in Fig. 9.7.

Asbestos, another remarkably useful inorganic material, is a hydrated magnesium silicate. One common variety (chrysotile) corresponds approximately to $3MgO \cdot 2SiO_2 \cdot 2H_2O$. Common asbestos and a few closely related minerals of the amphibole and serpentine groups are fibrous in nature. The fibers vary in length from a few tenths of an inch to well over an inch, the long-fiber variety naturally being preferred technically. These fibers are composed of crystals with one axis, along which stretches an indefinite chain of alternate silicon-oxygen-silicon atoms, parallel to the fiber bundle. Crystallization can be observed to be imperfect in one direction—a rare phenomenon in minerals, but common among organic substances (e.g., cellulose). The fibrous structure, combined with nonflammability, makes asbestos peculiarly suited for thermal and electrical insulation and, properly compounded, for many structural purposes.

9.10 CARBIDES

In silicon carbide (SiC) and boron carbide (B_4C), the binding forces are predominantly homopolar, rather than ionic. The hard, abrasive quality of such structures is associated with high symmetry and close packing of the constituent atoms. Silicon carbide is produced in an electric furnace at temperatures around 2000 C (3600 F), and once formed, is stable up to this temperature. Boron carbide, produced at 2500 C, is stable up to similarly high temperature.

9.11 GLASSES

Lack of crystallinity frequently recommends an inorganic material for industrial purposes. Fused quartz is an excellent example. Quartz

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* For definitions of these terms, see Chapter 10.
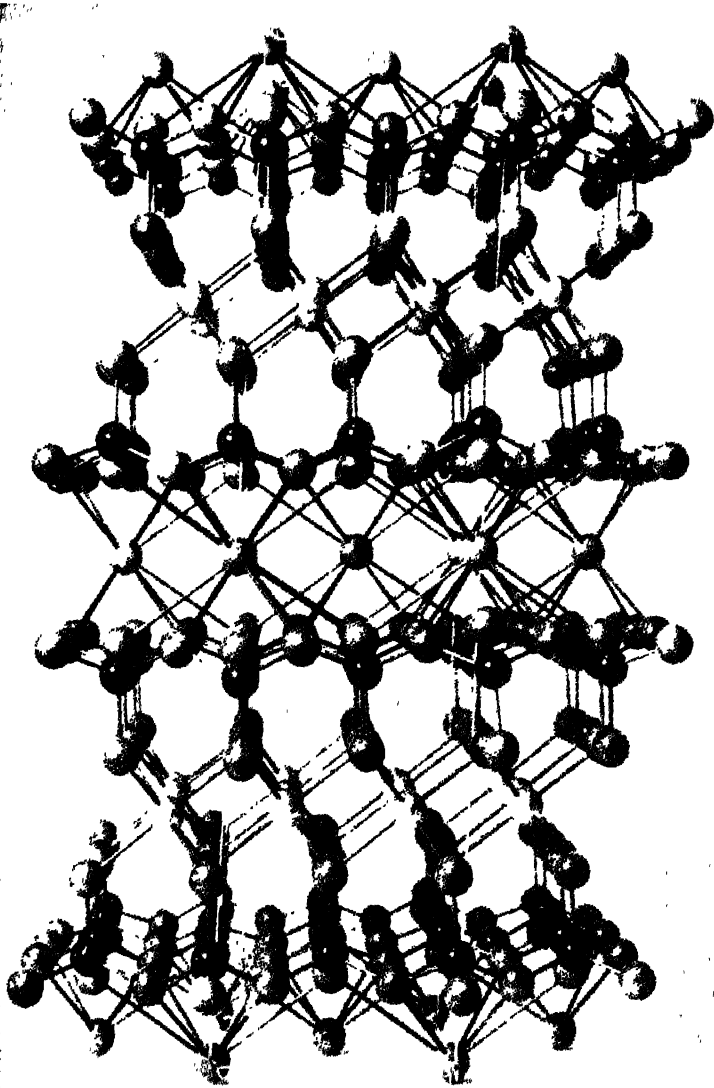
FIG. 9.7. Schematic representation of the structure of mica, according to W. L. Bragg. The unit cell is outlined by the fine lines that form a rectangle from the two topmost atoms to the opposite two at the bottom. (*From Atomic Structure of Minerals, by W. L. Bragg, Cornell University Press, Ithaca, New York, 2nd printing, 1950.*)

can be cooled from the melt without crystallizing. X-ray studies show that the arrangement in fused quartz involves three-dimensional interlocking rings, and that this arrangement is not entirely regular. This is typically a "glassy" structure, and, as a glass, fused silica can be formed into tubes, rods, or other shapes.

The term "glass" is, in fact, applied to many substances that can be solidified without crystallization and so maintained indefinitely. In typical glasses, analysis discloses the presence of extensive atomic and molecular networks lacking both in symmetry and in regular repetitiveness. During the formation of a glass, too, it is often possible to observe a region in the cooling curve where the melt viscosity, density, and heat capacity increase very rapidly. It is supposedly within this abnormal temperature range that solidification to a glass takes place.

Ordinary glasses are obtained by the fusion of oxides of silicon, calcium, magnesium, lead, aluminum, beryllium, the alkali metals, phosphorus, boron, and a few less common metals. The chemical identity of the compounds formed cannot always be precisely determined. Basically, however, metal oxides combine with silica, causing replacement of oxygen bridges by other polar groups, with progressive alterations in the physical properties of the silica. The network of bonded atoms remains highly extended in three dimensions. Both covalent and ionic bonding are found, as well as indefinite or intermediate types. The failure to crystallize is at least partially attributable to the extremely high viscosity of the melt, so that orientation and crystal growth are highly inhibited. If crystallization eventually occurs (devitrification), the glass loses many of its desirable properties.

One commonly accepted view of the somewhat irregular arrangement of atoms in a silicate glass is shown in Fig. 9.8. It is to be noted that the atomic distances and spatial relations are not very different from those of a crystalline silicate. The lack of exact regularity is, however, sufficient to account for the considerably different properties of the glasses. The strength and optical clarity of glasses are associated with this randomness of structure, coupled with microscopic uniformity (lack of faults and cleavage planes which are present in most crystalline materials). On the other hand, the presence of structures of very high molecular weight must also play an important role, because amorphous structures of low molecular weight (for example, those present in ordinary rosin and in "caramelized" sugar) are notoriously without strength, permanence, or optical clarity.
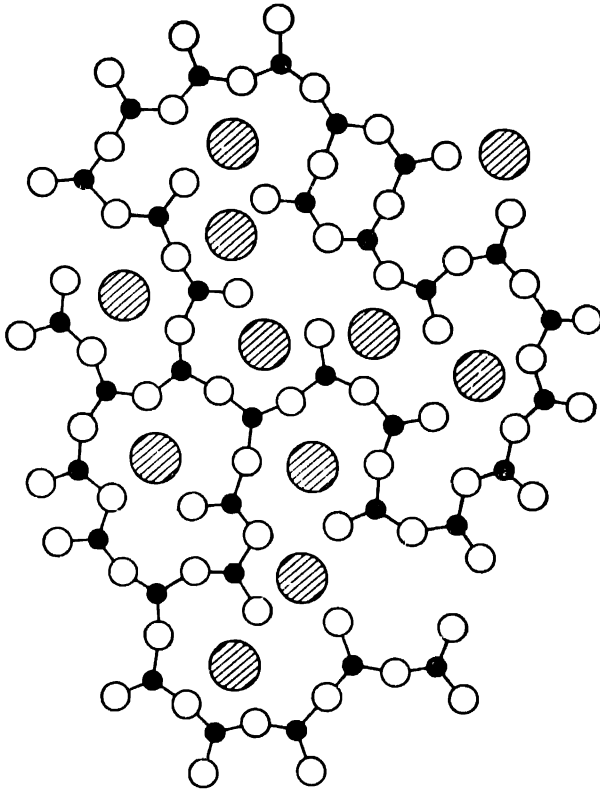
Fig. 9.8. Representation of the arrangement of atoms in a typical glass, after Zachariasen.

● Si   silicon atoms

○ O   oxygen atoms

◢ Na   metal atoms
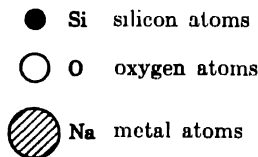
(By permission, from Physical Chemistry, by Eastman and Rollefson, McGraw-Hill Book Co., New York, 1947.)

9.12   CERAMIC MATERIALS

The term "ceramics" applies to a variety of inorganic products characterized by the high-temperature treatment universally employed during their manufacture. The principal raw material concerned is clay; but since clays differ widely in their composition, purity, firmness, plasticity, fusability, and other properties, the term is a wide and frequently misused one. The clays alone or mixed

with silica, flint, feldspar, etc., are fired in kilns at temperatures frequently in excess of 2000 F (1050 C), then cooled slowly.

The characteristics of clays that are of primary interest to the ceramics industry are frequently less their exact chemical composition than their colloidal properties, such as particle size, shape, nature of surface, plasticity, and *thixotropy*. Thixotropy is a property common to many colloidal systems. It is this property which enables some suspensions and gels to be converted (reversibly) by mechanical agitation to fluids of relatively low viscosity. A dilute bentonite gel provides a common example. Ordinary paints also are thixotropic; this allows them to flow readily when agitated by brushing but to increase greatly in viscosity as the brush is lifted. It is reasonable to assume from such behavior that the physical structure of thixotropic suspensions is altered by shear. The possibility of such alteration is greater when irregularly shaped particles are present. The fact that elongated, platelike particles are found in some highly thixotropic clay suspensions is in accord with this conception. With pottery or china, the importance of thixotropy can easily be appreciated, since the clay suspensions used must be very carefully balanced to flow evenly, yet to "set" properly during firing.

Common products of the ceramics industries are china, porcelain, porcelain enamel, ceramic tile, firebrick, high-temperature inorganic insulating materials, electrical conduit, ordinary brick, tile and clay pipe, chemical stoneware, etc. Refractories are other important products of the ceramics industry. Because they must have very high melting points, and since impurities lower the melting point, they are almost always pure substances. Common examples are alumina (Al_2O_3), zirconia (ZrO_2), magnesia (MgO), iron chromite ($FeCr_2O_4$), silicon carbide (already mentioned) and, of course, silica.

Structure of Organic Materials

Organic chemistry concerns itself with nearly a million individual, distinguishable compounds. The only certain common denominator is the presence of at least one atom of carbon in each. One function of this branch of chemistry is, of course, to establish intelligible relations within this otherwise vast and unwieldy subject matter.

9.13 ORGANIC MATERIALS

The homopolar or covalent bond is the "intrinsic mortar" that holds most organic compounds together. Carbon, situated in the fourth group and in the first short series of the periodic table (Fig. 9.2) is,
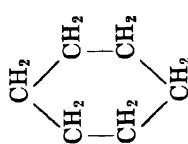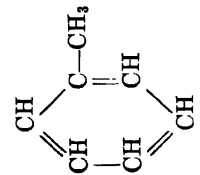
in a sense, the most "neutral" of elements. It accepts and donates electrons with equal facility. Because this process of "sharing" electrons may be repeated over and over again, it is possible to build up an exceeding variety of molecules, including many very large or "giant" molecules. Such macromolecules are both the end result of many important vital processes (hemoglobin, proteins, cellulose, keratin, silk, and natural rubber are a few common examples) and of many commercially important synthetic processes (of which synthetic rubber, Nylon fibers, alkyd paint finishes, and phenolic plastics are examples).

The structure of organic compounds may be illustrated by a few typical examples listed in Table 9.1.

In the above structures only homopolar bonds are indicated. Molecular weights are the arithmetic sum of the atomic weights involved. Most of these compounds are neutral, but diethyl amine and pyridine are basic, butyric acid is acidic, and polyglycine contains both acidic (—COOH) and basic (—NH₂) groups. Organic acids and bases form ions in conducting media, ordinarily through electrolytic dissociation. Salts that are obtained on evaporation of such solutions may, in certain simple cases, crystallize in typically ionic systems. However, most simple organic compounds form molecular lattice crystals. With simple organic compounds, as was stated above, the points on the crystal lattice are usually occupied by molecules, or by segments of molecules. The molecules are held in the crystal by lattice forces which are similar to, if not identical with, van der Waals forces. In crystals of aliphatic compounds, structures related to that of diamond are frequently detected.* The tetrahedral valence bonds of carbon are characteristic of most aliphatic compounds, and often provide one important element of crystal symmetry. For aromatic compounds, the basic building stone is the six carbon benzenoid ring, as it is known to exist in graphite.* These six carbon atom rings are almost invariably planar, and the forces between them are weak, corresponding again to secondary valence or van der Waals forces. The more complex aromatic molecules approach most nearly to the actual graphite structure. When polar groups such as hydroxyl, aldehyde, ketone or halogen are present in organic molecules, the molecules pack together more closely in the crystal, owing to the stronger intermolecular forces such groups exert. When even more highly polar groups are present, such as the carboxyl or amino groups, and more especially their salts, genuine electrostatic forces may come

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* The crystal structures of diamond and graphite are shown in Fig. 9.10.

Table 9.1   Examples of the Structure of Organic Compounds

Compound	Structure	Type	Descriptive Notes
Propane	$CH_3CH_2CH_3$	Saturated aliphatic hydrocarbon	Representative of a large number of open-chain compounds that contain only carbon and hydrogen, all having the generic formula C_nH_{2n+2}. Generally they are rather stable, except towards oxidation and thermal decomposition ("cracking").
1-Pentene	$CH_3CH_2CH_2CH=CH_2$	Unsaturated aliphatic hydrocarbon	Contain less hydrogen than the above type. The unsaturation increases chemical reactivity.
Cyclohexane		Cycloaliphatic hydrocarbon	Representative of saturated closed-ring hydrocarbons. The reactivity is similar to that of open-chain analogues.
Toluene		Aromatic hydrocarbon	"Aromatic" signifies the presence of a closed ring of atoms of particular and peculiar reactivity. Although low in hydrogen content, they are not "unsaturated" in the same sense as are similar open-chain compounds and, they are more stable towards oxidation and "cracking." The hydrogens are more easily replaced by other atoms or groups.

Ethanol	CH_3CH_2OH	Alcohol	Representative of hydroxyl (OH) derivatives of saturated aliphatic hydrocarbons. The OH group is a center of reactivity. Relatively easily oxidized. The OH group is replaced by other groups fairly easily.
Ortho cresol		Phenol	Phenols are "aromatic alcohols." They are also weak acids. The hydroxyl group vastly increases the ease of replacement of the ring hydrogens by other groups.
Formaldehyde		Aldehyde	Aldehydes are oxidation products of alcohols. They are in turn easily oxidized to acids; easily reduced to alcohols. They react readily with a variety of other molecules, including alcohols, phenols, amines, amides, etc., to form more complex compounds.
Acetone	$CH_3-\overset{\overset{\displaystyle O}{\|\|}}{C}-CH_3$	Ketone	Similar to aldehydes, but less reactive.
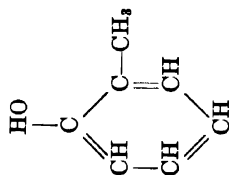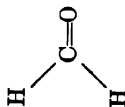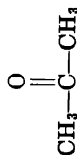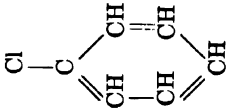
Table 9.1   Examples of the Structure of Organic Compounds (Continued)

Compound	Structure	Type	Descriptive Notes
Butyric acid	$CH_3CH_2CH_2C(=O)-OH$	Acid	Representative of organic acids. Relatively weak compared to mineral acids. Oxidation products of alcohols and of aldehydes. Relatively stable and very difficult to reduce. The hydrogen of the carboxyl group (COOH) is replaceable by various groups, giving esters, acid anhydrides, acid chlorides, etc. Carboxylic acids form salts with alkalis or organic bases.
Diethyl ether	$CH_3CH_2-O-CH_2CH_3$	Ether	Formally, ethers are "anhydrides" of alcohols (anhydride = minus water). They are relatively unreactive. Some ethers are useful as solvents.
Chlorobenzene	(benzene ring with Cl)	Aromatic halide	Halogen derivative of aromatic hydrocarbon. Relatively stable towards heat, light, and most chemicals.
Diethyl amine	$CH_3CH_2NCH_2CH_3$ (with H)	Amine	Amines are organic derivatives of ammonia. Three general types: primary, RNH_2; secondary, R_2NH; tertiary, R_3N. [R represents any hydrocarbon group, such as methyl (CH_3), ethyl (C_2H_5), phenyl (C_6H_5).] Amines are roughly of the same basicity as ammonia. They form salts with organic and inorganic acids.
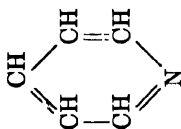
Name	Structure	Category	Description
Pyridine	(ring: CH=CH, CH=CH, CH, N)	Aromatic heterocyclic amine	"Heterocyclic" indicates a ring of atoms including at least one atom other than carbon. Pyridine is a tertiary amine (see above), since all three valences of nitrogen are occupied with carbon.
Polyisobutylene	$-CH_2-\underset{CH_3}{\overset{CH_3}{C}}-\left[CH_2-\underset{CH_3}{\overset{CH_3}{C}}-\right]_n$	Polymeric hydrocarbon	A polymer contains a large number of identical repeated units. Here the repeated unit is $-CH_2-C(CH_3)_2-$, related to the "monomer," isobutylene (i.e., $CH_2=C(CH_3)_2$) from which the polymer is formed. Polymers are generally mixtures. The average molecular weight depends on the average value of n.
Polyglycine	$NH_2\left[\overset{O}{\overset{\|}{CH_2C}}-NH\right]_n-\overset{O}{\overset{\|}{CH_2C}}-OH$	Polypeptide (polyamide)	Polypeptides are related closely to the building blocks of the proteins. They are also polymers. The "monomer" in this case is glycine, NH_2CH_2COOH, both an amine and an acid; i.e., an aminoacid. The polymer has one amino group and one acid group for every n amide ($-CONH-$) groups.
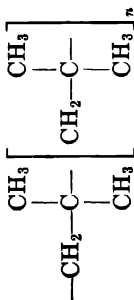
into play. Since these forces are of the same order of magnitude as those that operate in ionic crystals, they cannot always formally be distinguished from them. Depending upon the size and shape of the purely organic part of the molecule, relative to these strong polar groups, the total crystal will assume a configuration somewhere intermediate between that of a purely ionic and that of a purely molecular crystal. The resulting structure is often highly complex. Since there are only incomplete analytical data for many such crystal systems, significant structural details cannot often be found.

9.14 PETROLEUM AND NATURAL GAS

Petroleum deposits of the simplest type ("Pennsylvania crudes") are predominantly complex mixtures of aliphatic saturated hydrocarbons, of which the simple generic formula is C_nH_{2n+2}. In natural gas, which is frequently associated with petroleum deposits, the simplest members of this series are found. These are methane CH_4, ethane C_2H_6, propane C_3H_8, and butane C_4H_{10}. These hydrocarbon gases are also sometimes present in crude oil, along with numerous higher members of the series. Individual members up to heptacontane, $C_{70}H_{142}$, have been synthesized. On distillation of petroleum, various "fractions" are obtained, ranging from volatile "petroleum spirits" through gasoline, kerosene, fuel oil, and lubricating oils to semi-solid and solid Vaseline and paraffin wax fractions. Many oil fields contain a much lower fraction of straight-chain aliphatic hydrocarbons and a higher proportion of asphaltic components than do Pennsylvania crudes. The asphaltic components contain, as major constituents, cyclic aliphatic hydrocarbons—the so-called naphthenes. Examples are dimethyl cyclopentane and ethyl cyclohexane, see Fig. 9.9. Many petroleum crudes also contain a considerable percentage of aromatic hydrocarbons.
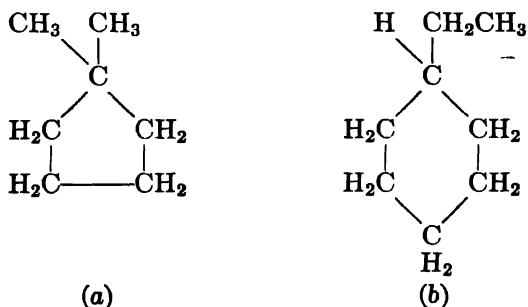
Fig. 9.9. Schematic structure of (a) 1,1-dimethyl cyclopentane, and (b) ethyl cyclohexane.

9.15 COAL TAR

When coal is subjected to coking (a process involving "destructive distillation"), gaseous and liquid products are obtained in addition to coke. The crude liquid, called coal tar, when subjected to fractional distillation and purification, yields a variety of useful products—neutral, acidic, and basic. The neutral products include a series of cyclic aromatic hydrocarbons. The unsaturation of aromatic compounds, as indicated previously, is of a special type, since these hydrocarbons are in general very stable, thermally and towards many chemicals. Examples are benzene C_6H_6, toluene C_7H_8, xylene C_8H_{10}, cumene C_9H_{12}, naphthalene $C_{10}H_8$, and anthracene $C_{14}H_{10}$. Note the low ratio of hydrogen to carbon compared to the saturated paraffins, C_nH_{2n+2}.

The acidic components of coal tar contain a mixture of phenols, which are hydroxy derivatives of the aromatic hydrocarbons. Examples are phenol (carbolic acid) C_6H_5OH, cresol C_7H_7OH, xylenol C_8H_9OH, and naphthol $C_{10}H_7OH$.

The basic compounds present in coal tar are principally heterocyclic aromatic amines. The most important members are pyrrole C_4H_5N, pyridine C_5H_5N, picoline C_6H_7N,* lutidine C_7H_9N,* quinoline C_9H_7N, and carbazole $C_{12}H_9N$.

The predominance of carbon-carbon bonded cyclic structures in coal tar distillates suggests that this linkage is present in the original coal, and this has been partially confirmed experimentally. Carbon has a valence of 4 and, if bonded symmetrically, an indefinite structure of close-packed, equispaced carbon atoms at normal, or "tetrahedral-valence," angles to one another can be visualized. Such a structure undoubtedly exists imperfectly in carbonaceous deposits, highly modified by partial hydrogenation, chain rupture, and other changes. In diamond, which is nearly pure, crystalline carbon, this ideal structure is, in fact, realized. Diamond belongs to the isometric crystal system and shows fourfold (i.e., regular, tetrahedral) coordination in its space grouping of atoms. In graphite, which is an allotropic form of diamond, the carbon atoms are arranged in flat planes.

* There are 3 isomeric picolines, which differ only in the position of a methyl group with respect to the ring nitrogen atom. Similarly, there are six isomeric lutidines, differing from one another in the positions of two methyl groups with respect to one another and to the ring nitrogen atom. This common type of isomerism, called position isomerism, illustrates one of the many complexities of organic structural chemistry, and suggests why so many distinct compounds exist.

(a)

(b)
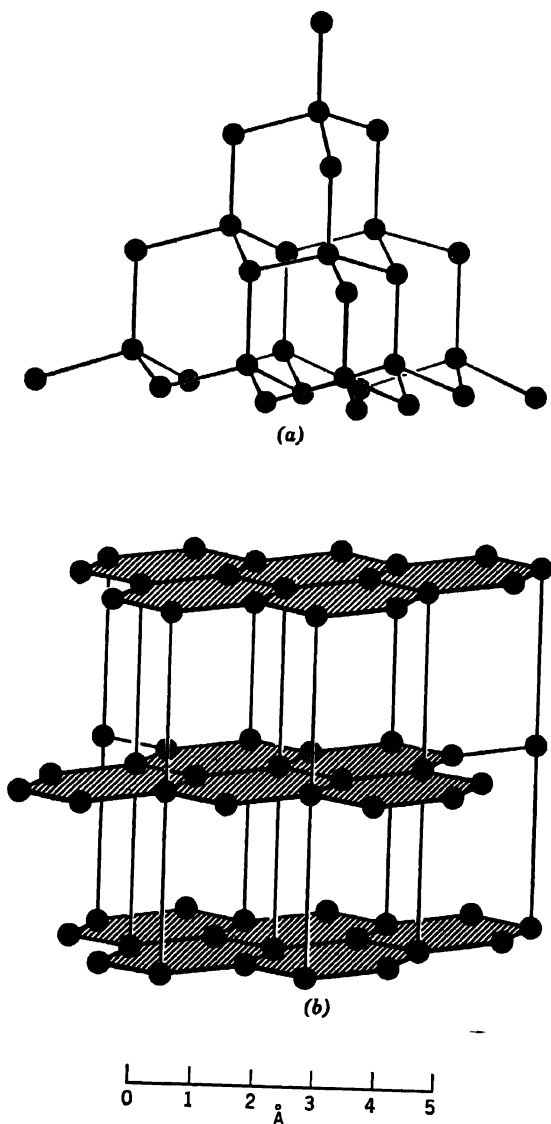
Fig. 9.10. (a) The crystal structure of diamond. The carbon atoms are virtually in contact, with a distance between carbon centers of 1.54 A. (b) The crystal structure of graphite. The fine horizontal lines join atoms of successive sheets which are in the same vertical relationship. The carbon-carbon distance in the planes is 1.42 A; that between planes is 3.40 A. (*From Atomic Structure of Minerals, by W. L. Bragg, Cornell University Press, Ithaca, New York, 2nd printing, 1950.*)

Related groupings of 6 carbon atoms each can be identified. The relatively weak van der Waals forces between parallel planes help account for the platelike fracture and slipperiness of graphite.* Schematic representations of the crystal structures of diamond and graphite are shown in Fig. 9.10.

9.16 CARBOHYDRATES

The carbohydrates constitute a large group of molecules, widely distributed in nature, which contain only carbon, hydrogen and oxygen. The simplest carbohydrates are sugars: for example, glucose, which contains a ring of 5 carbon atoms and 1 oxygen (see Fig. 9.11).
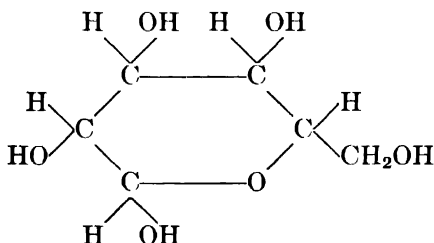
Fig. 9.11. Schematic structure of glucose.

Cellobiose, obtained by careful hydrolysis of cellulose, has 2 glucose units linked together through an oxygen atom (see Fig. 9.12). The
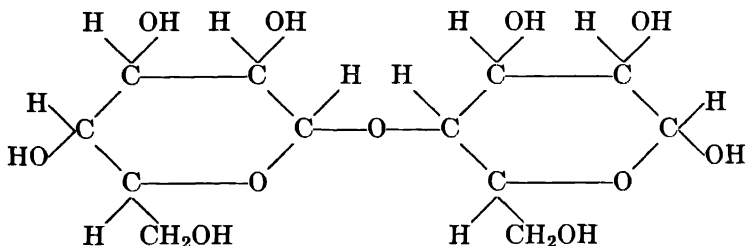
Fig. 9.12. Schematic structure of cellobiose.

starches and celluloses contain many such simple sugar units linked together by oxygen (Fig. 9.13). The application of X-ray analysis to cellulose and related carbohydrates has been of great help in establishing their intimate structures. A high degree of crystallinity is

*The inorganic, high-melting solid, boron nitride (BN), which has a structure very similar to that of graphite, is also so similar to it physically that it has earned the name "inorganic graphite."

found in native cellulose specimens. Fig. 9.4 shows that the unit crystallographic cell contains four simple glucoselike units. These simple units correspond empirically to $C_6H_{10}O_5$ and cellulose is accordingly $(C_6H_{10}O_5)_x$, where x may be 1000 to 10,000. It has already
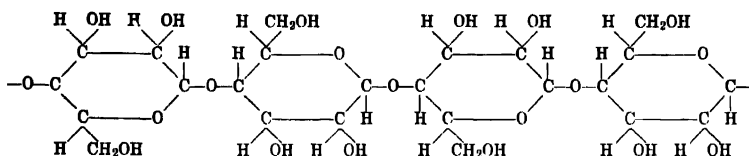
FIG. 9.13. Schematic structure typical of starches and cellulose.

been shown that the crystalline regions, or crystallites, in cellulose are composed of bundles of chains (micells) oriented approximately parallel and separated by amorphous areas. The average diameter of a micellar unit is about 60 Angstrom units (60×10^{-8} cm), which corresponds to an area including between 100 and 200 molecular chains. The average length of the micellar units is about 600 Angstrom units. The remarkable properties of cellulose are partially a result of the presence of such imperfectly oriented fiber bundles.

9.17 SHELLAC

The lac insect, *Tachardia lacca*, produces a viscous exudation from certain sap trees native to India. When refined, this becomes lac resin, called shellac. The lac resin contains a mixture of polyhydroxy acids and esters, components of which are aleuritic acid $C_{15}H_{28}(OH)_3$-COOH, shellolic acid, $C_{13}H_{16}(OH)_2(COOH)_2$, and an ester of formula $C_{32}H_{54}O_9$. Shellac is useful as a surface coating because, on standing (drying), the hydroxyl (OH) and carboxyl (COOH) groups take part in esterification reactions; that is, they combine with one another, with loss of water, to form esters:

$$RCOOH + R'OH \rightarrow RCOOR' + \overline{H}_2O$$
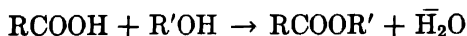
This causes the molecular weight to be built up considerably. The resulting structures (polyesters) are much less sensitive to moisture and solvents than are simple esters, although perhaps still not entirely satisfactory in this respect. Since shellac is a good adhesive, has a low dielectric constant, and resists carbonization, it is widely used with fillers such as flake mica and asbestos, and as an impregnant

with cotton or glass cloth for electrical insulation (Hercolite cylinders, varnish cambric, commutator slot compound, and the like).

9.18 NATURAL FIBERS

Among naturally occurring fibers, cotton is cellulosic in structure. The repetitive polysaccharide structure has been described above. Silk and wool are examples of natural protein fibers. Both consist of long chains of polypeptidelike units. These may be represented sche-

matically as $-R-\overset{\overset{O}{\|}}{C}-NH-R'-\overset{\overset{O}{\|}}{C}-NH-R''-\overset{\overset{O}{\|}}{C}-NH-R'''-$, where R, R', R'', etc., are groups derived from the various amino acids that are known to occur in nature, for example: glycine NH_2CH_2COOH, alanine $CH_3\underset{\underset{NH_2}{|}}{C}HCOOH$, serine $HOCH_2\underset{\underset{NH_2}{|}}{C}HCOOH$, valine $(CH_3)_2CH\underset{\underset{NH_2}{|}}{C}HCOOH$, cystine $HSCH_2\underset{\underset{NH_2}{|}}{C}HCOOH$, tyrosine $HOC_6H_4CH_2\underset{\underset{NH_2}{|}}{C}HCOOH$, etc.

9.19 NATURAL RUBBER

Natural rubber is obtained in the form of a latex from the sap of *Hevea brasiliensis* and a few other plants. The latex contains spherical colloidal particles in the range of 0.1–2 mu in diam. Crude rubber is coagulated by heat or by addition of electrolytes. Pure gum rubber is a hydrocarbon of empirical composition $(C_5H_8)_x$, where x is usually over 1000. The rubber molecule consists of coiled up, linear chains of multilinked isoprene units (Fig. 9.14). Certain in-

$$-CH_2-\underset{\underset{CH_3}{|}}{C}=CH-CH_2-\left[CH_2-\underset{\underset{CH_3}{|}}{C}=CH-CH_2\right]_n-$$

Fig. 9.14. Schematic structure of multilinked isoprene unit that forms linear chains in natural rubber molecules.

versions of this regular arrangement sometimes occur. Geometric space relations are also of great importance, since gutta-percha, which has the same chemical structure as rubber but differs in the spatial arrangement of the individual isoprene units, is hard and

horny and exhibits low elasticity. The reversible extensibility and the vulcanizability of rubber are associated with the length of the linear chains, the geometric relations, and the presence of the unsaturated linkage in each isoprene segment. In the long search for rubber substitutes, these considerations have been kept in mind, and the natural rubber molecule has served as a model for many of the synthetic materials.

9.20 SYNTHETIC RESINS

A basic aim of synthesis in the field of high polymers has been to reproduce and improve on the properties of natural resins, fibers, and rubber. A better understanding of these naturally occurring materials has contributed vastly to the plastics industry and to the utilization of high-molecular-weight organic materials in industry generally.

Vinyl Polymers. This important group of synthetic high polymers is obtained by a process known as addition polymerization. Vinyl monomers are usually simple unsaturated molecules having the general structure, $CH_2{=}CHX$, where X may be any of a large number of atoms or groups. The first step in the polymerization process (*initiation*) consists in activating the vinyl monomer, by addition of energy, of a free radical, or of an ionic catalyst such as $AlCl_3$ or BF_3.

$CH_2{=}CHX \xrightarrow{\text{energy}} CH_2{=}CHX *$ (a transitory, energy-rich intermediate), or $CH_2{=}CHX + R \cdot \rightarrow RCH_2CHX \cdot$ (a free organic radical intermediate) or $CH_2{=}CHX + MeCl_3 \rightarrow \overset{-}{Me}Cl_3CHXCH_2\overset{+}{}$ (an active ionic intermediate).

In the second step (*growth*), many units of the monomer combine to propagate a growing chain. This is formulated as follows for the free radical mechanism:

$$RCH_2CHX \cdot + n(CH_2{=}CHX) \rightarrow RCH_2CHX(CH_2CHX)_n \cdot$$
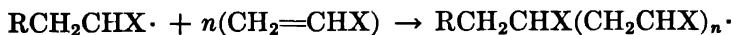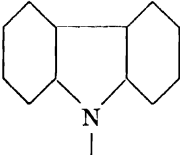
The final step (*termination*) involves elimination of the active center by abstraction of energy, removal of ionic charge, or mutual destruction of free radicals in pairs, by reaction with one another, or through some formally similar mechanism.

$$RCH_2CHX(CH_2CHX)_n \cdot + RCH_2CHX(CH_2CHX)_m \cdot \rightarrow$$
$$RCH_2CHX(CH_2CHX)_n(CHXCH_2)_mCHXCH_2R$$
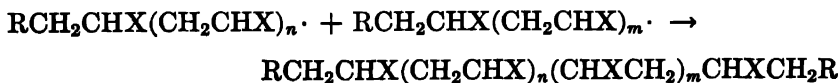
Important examples of vinyl polymers are listed in Table 9.2.

Table 9.2   Examples of Vinyl Polymers

Polymer	*X*	*Type*
Polyethylene	H	Hydrocarbon
Polyvinylchloride	Cl	Alkyl halide
Polyvinylacetate	$\overset{\displaystyle O}{\overset{\displaystyle \|}{O—C—CH_3}}$	Ester
Polystyrene	C_6H_5	Hydrocarbon
Polymethyl acrylate	$\overset{\displaystyle O}{\overset{\displaystyle \|}{C—OCH_3}}$	Ester
Polyacrylonitrile	$C{=}N$	Nitrile
Polyvinyl carbazole		Aromatic amine

Occasionally, more than one hydrogen of the ethylene monomer is substituted by an "X" group, as in the following:

$$\left[-CH_2-\underset{\underset{CH_3}{\displaystyle |}}{\overset{\overset{CH_3}{\displaystyle |}}{C}}- \right]_n \qquad \text{Polyisobutylene}$$

$$\left[-CH_2-\underset{\underset{Cl}{\displaystyle |}}{\overset{\overset{Cl}{\displaystyle |}}{C}}- \right]_n \qquad \text{Polyvinylidene chloride}$$

$$(-CF_2CF_2-)_n \qquad \text{Polytetrafluoroethylene}$$

$$(-CFClCF_2-)_n \qquad \text{Polychlorotrifluoroethylene}$$
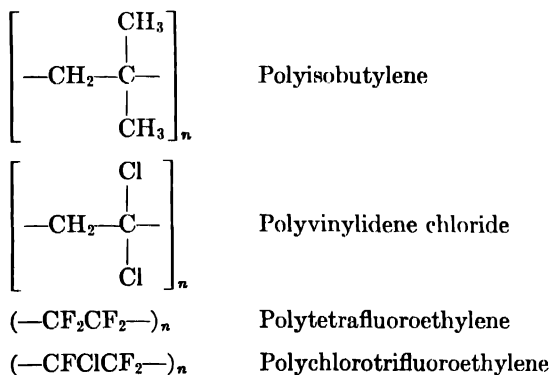
Copolymers. Frequently, two or more monomers are caused to polymerize together. Usually a random interpolymer (copolymer) is formed. The typical structure of a copolymer is as follows:

$$-CH_2CHXCH_2CHYCH_2CHXCH_2CHXCH_2CHY-$$

but in special cases the monomer units may alternate regularly, as in

$$-CH_2CHXCH_2CHYCH_2CHXCH_2CHY-$$

By choosing the proper components, proportions, and conditions of polymerization, optimum properties may be achieved for the systems involved. Thus, with vinyl chloride and vinyl acetate, the copolymers ("Vinylite") are more versatile and more useful than either of the homopolymers, or physical mixtures of the two.

Uses of the Vinyl Polymers. The vinyl polymers are exceedingly versatile materials and accordingly find numerous uses in industry and in the domestic economy. Some of the principal uses of important polymers are listed in Table 9.3.

Table 9.3 Some Important Polymers and Their Uses

Polymer	Outstanding Properties	Applications
Polyethylene	Water resistance Toughness Low dipole movement Low electrical loss factor	Electrical insulation Coaxial cable Packaging Moisture-proofing Coating ice-cube trays
Polyisobutylene	Flexibility Moisture resistance Elasticity	"Butyl" rubber Bullet-proof tanks Pour-point depressors Cable coatings
Polyvinylchloride	Plasticizability Low flammability Flexibility Toughness	Cable jackets Lead-wire insulation Rubber substitute Fabric coating
Polyvinyl ethers	Pressure sensitivity Solubility	Pressure-sensitive tapes
Polyvinylidene chloride	Solvent resistance Acid resistance Toughness Nonflammability	Woven fabrics Seat covers and upholstery Acid-resistant tubing Belts and gaskets
Polystyrene	High resistivity Low dielectric constant Moisture resistance Chemical resistance	Electrical insulation Radar components Lenses Instrument panels Refrigerator-cabinet components
Acrylic polymers	Transparency Clarity Conformance to shape	Lenses Airplane covers and shields Costume jewelry
Polyvinyl carbazole	Acid and alkali resistance Low power factor Thermal resistance	Capacitor material Electronic parts Mica bonding

Condensation Polymer. This class of synthetic high polymers is formed by a reaction that may be formally represented as the repetitive elimination of small molecules from two or more reacting species, as follows:

$$n(X—R—X) + n(Y—R'—Y) \rightarrow (—R—R'—)_n + 2n(XY)$$
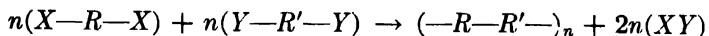
If at least one of the reacting species contains more than two reactive groups (*"functionality"* greater than 2), the resulting chain molecule can grow in more than two directions. This results in a three-dimensional or cross-linked structure. Glyceryl phthalate is a common example. The reaction proceeds in steps, schematically, as shown in Fig. 9.15.

As the reaction continues, polymer growth occurs, both linearly and by cross linking. The growing molecules finally reach a size and complexity such that they can effectively react no further. This is the gelation point, and is frequently associated with abrupt changes in viscosity as well as with rapid changes in molecular weight and complexity.

9.21 THERMOPLASTIC AND THERMOSETTING RESINS

A common and useful classification of polymers is into "thermoplastic" and "thermosetting" types. It must be recognized, however, that this differentiation accounts only for one set of extremes in the gross behavior of such materials. Many high-molecular-weight substances cannot be distinguished unequivocably in this respect. Truly thermoplastic polymers have definite melting or softening points, and are capable of reversible thermal changes. They are likewise capable of complete solution in suitable solvents, although such solutions often are highly viscous. Many vinyl polymers are thermoplastic. Condensation polymers produced from reacting components with functionalities no greater than 2 are also thermoplastic. When cross linking can occur, through any cause, and three-dimensional networks are formed, thermosetting polymers result. Such products do not melt below their decomposition temperatures, and have very limited solubilities and low swelling tendencies. Once cured, thermosetting polymers are no longer capable of reversible thermal changes. Nor can the chemical reactions by which they are formed in general be reversed. Thermosetting resins are therefore relatively stable, not only thermally, but chemically and mechanically as well. In practice, of course, many high polymers are encountered whose behavior is neither entirely that of a thermoplastic nor that of a thermosetting

HOCH$_2$CHCH$_2$OH + (ring)COOH $\xrightarrow{-H_2O}$
    OH   COOH

HOCH$_2$CHCH$_2$OCO–(ring) $\xrightarrow[+G.]{-H_2O}$
    OH
        COOH

HOCH$_2$CHCH$_2$OCO(ring)
    OH
      COOCH$_2$CH–CH$_2$OH $\xrightarrow[+P.A.]{-H_2O}$
           OH

HOCH$_2$CHCH$_2$OCO(ring)
    OH
      COOCH$_2$CHCHOCO–(ring) $\xrightarrow[+G]{-H_2O}$
          OH
             COOH

HOCH$_2$CHCH$_2$OCO(ring)
    OH
      COOCH$_2$CHCH$_2$OCO–(ring)
          OH
            COOCH$_2$CHCH$_2$OH $\xrightarrow[+P.A.]{H_2O}$
               OH

HOCH$_2$CHCH$_2$OCO–(ring)
    OH
      COOCH$_2$CHCH$_2$OCO–(ring)
          O
          CO
               COOCH$_2$CHCH$_2$OH $\xrightarrow[\substack{+2nd\ growing\\chain}]{-H_2O}$
          HOOC(ring)   OH

HOCH$_2$CHCH$_2$OCO–(ring)
    OH
      COOCH$_2$CHCH$_2$OCO(ring)
          O
              COOCHCH–CH$_2$OH
           CO   OH

–OCH$_2$CHCH$_2$OCO(ring)
    OH
            O=C
              O
      COOCH$_2$CHCH$_2$OCO(ring)
               COOCH$_2$CHCH$_2$OCO(ring)
                  OH   COOCH$_2$— etc.

Fig. 9.15. Schematic representation of cross polymerization of glyceryl phthalate   G = glycerol. P.A. = phthalic acid.

resin. This is not unexpected, considering the complex nature of the chemical reactions involved.

Technically it is important to carry out polycondensation reactions so that the gel point is reached at a predetermined and controllable time: for example, when the polymer is about to be ejected from a compression mold, injection mold, or extruder. A number of important condensation polymers are described in Table 9.4.

9.22 CELLULOSE PLASTICS

Raw cellulose is practically useless as a plastic, except as a filler in the form of wood flour, cotton flock, or rag stock. Regenerated cellulose, however, which is prepared by solution and controlled reprecipitation of purified cotton, is exceedingly useful as a packaging material (Cellophane). Under similar conditions, regenerated cellulose can be drawn into fibers (rayon). Cellulose plastics, in the strict sense, are based upon chemically treated cellulose. The reactions involved are principally esterification and etherification; the products, therefore, are cellulose esters and ethers. Prominent examples are cellulose nitrate (nitrocellulose), cellulose acetate, cellulose propionate, cellulose acetate-butyrate, methyl cellulose (Methocel), and ethyl cellulose. The reagents used attack the cellulose molecules at the free hydroxy groups present on the polysaccharide rings. Cellulose plastics are useful as safety films, surface coatings, hot-melt compositions, dispersing and emulsifying agents, transparent sheet, molding powders, aircraft enclosures, dielectric film and foil, imitation ivory, artificial leather, etc.

9.23 POLYVINYL ACETALS

Polyvinyl acetate is the basis of a series of important plastics obtained by hydrolysis and acetalization reactions. The hydrolysis product, polyvinyl alcohol, is used in film form as a packaging material. It is highly resistant to oils, fats, and many solvents. The acetals of polyvinyl alcohol contain the repetitive unit

$$—CH_2—CH—CH_2—CH—$$

with the O atoms joined to a CH group bearing R.
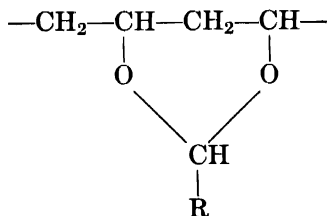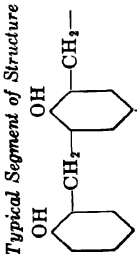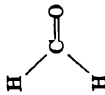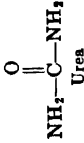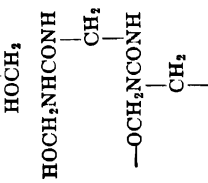
Table 9.4   Principal Condensation Polymers

Type	Common Reactants	Typical Segment of Structure	Outstanding Properties	Applications
Phenol–formaldehyde	Phenol (OH); meta-Cresol (OH, CH₃); Formaldehyde (H–C(=O)–H)		Moldability, Castability, High impact strength, Heat resistance, Low cost	Housings, Cabinets, Control panels, Telephones, Switch boxes, Containers, etc.
Urea–formaldehyde	Urea (NH_2–C(=O)–NH_2); Formaldehyde (CH_2=O)	$HOCH_2NHCONH$ ... CH_2 ... $-OCH_2NCONH$ ... CH_2- ... $HOCH_2$	Nontracking, Heat resistance, Fair electrical characteristics	Specialized uses as above, Adhesives, Baking finishes
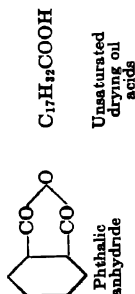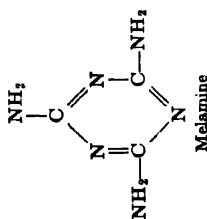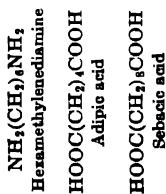
		Properties	Applications
Melamine— formaldehyde	Melamine; $CH_2=O$ Formaldehyde	Heat resistance High impact strength Tracking resistance Durability	Glass laminates (electrical insulation) Baking finishes Impregnants for plywood Textile finishes
Alkyd (polyester)	$HOCH_2CHOHCH_2OH$ Glycerol $HOCH_2CH_2OH$ Glycol Phthalic anhydride $C_{17}H_{32}COOH$ Unsaturated drying oil acids Shown in reaction scheme in preceding section	Versatility Drying capacity Compatibility with oils and solvents	Finishes for the automotive, refrigerator, furniture and other industries Paints Low-pressure laminates Rubber substitutes
Nylon (polyamide)	$NH_2(CH_2)_6NH_2$ Hexamethylenediamine $HOOC(CH_2)_4COOH$ Adipic acid $HOOC(CH_2)_8COOH$ Sebacic acid $-NH(CH_2)_6NH[CO(CH_2)_4CONH(CH_2)_6]_n-$	Toughness Elasticity Spinnability Heat resistance	Substitute for silk Artificial bristles Fishing line Wire insulation
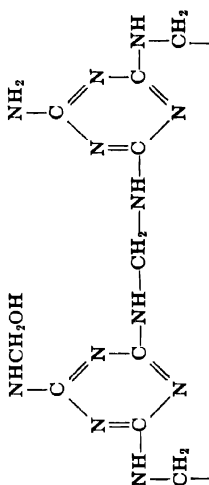
where R is usually H ("Formvar") or C_3H_7 ("Butvar"). "Formvar" is an unusually tough material, and has good flexibility and heat resistance and good electrical properties. "Formvar" serves as the most important basis for magnet-wire coatings, where a thin film of flexible, tough, thermally stable insulation is required. "Butvar" is used primarily as the inner plastic layer of safety glass, where toughness, moisture resistance, and flexibility are demanded.

9.24 SILICONES

The silicones represent a family of synthetic materials where the skeletal framework consists of alternate silicon and oxygen atoms, rather than carbon atoms, as follows:

$$
\begin{array}{cccc}
R & R & R & R \\
| & | & | & | \\
-Si-O-Si-O-Si-O-Si-O- \\
| & | & | & | \\
R & R & R & R
\end{array}
$$
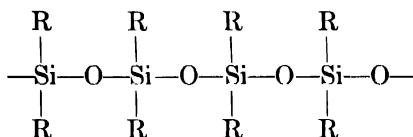
The R groups are organic and are subject to variation almost at will. Thermosetting resins are obtained when a functionality greater than 2 is introduced, just as in the better known organic polymers, as follows:

$$
\begin{array}{ccccc}
R & R & R & O & R \\
| & | & | & | & | \\
-O-Si-O-Si-O-Si-O-Si-O-Si- \\
| & | & | & | & | \\
R & O & R & O & R \\
\\
R & & R & R & R \\
| & | & | & | & | \\
-O-Si-O-Si-O-Si-O-Si-O-Si- \\
| & | & | & | & | \\
R & R & O & R & R \\
\end{array}
$$
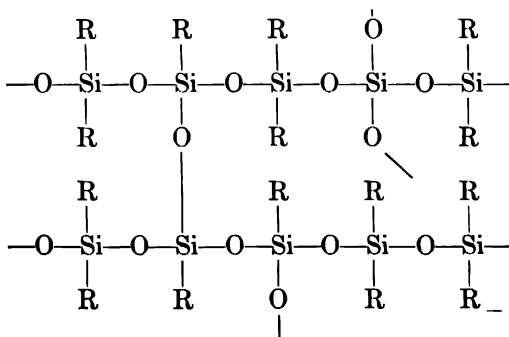
The silicon-oxygen (siloxane) skeleton confers the property of unusual heat resistance, especially if the organic R groups are small or in themselves are thermally stable. The silicones are finding uses in the electrical industry as high-temperature insulation, frequently in combination with glass cloth or fibers, mica, or asbestos. The silicones are also available as oils, rubbers, greases, waxes, and as liquids capable of depositing thin, water-repellent films.

9.25 SYNTHETIC RUBBER

Synthetic rubbers are based on the model of natural rubber and on that of the thermoplastic vinyl high polymers. In fact, there can be no precise distinction or exact line of demarcation drawn between vinyl polymers and synthetic elastomers. With proper choice of vinyl monomers (or comonomers) and proper choice of conditions, rubberlike elasticity can be achieved as the result of straight vinyl polymerization. This has already been noted with polyisobutylene, where the highest-molecular-weight polymers possess not only toughness, but marked extensibility and retractability as well. Useful synthetic elastomers are obtained by suitable combinations of selected monomers. Butadiene, related closely to the isoprene unit of natural rubber, is the commonest monomer. In G.R.-S. synthetic rubber it is copolymerized with styrene monomer; in G.R.-A. rubber the comonomer is acrylonitrile. The monomer structures are shown in Fig. 9.16.

$$CH_2\!=\!CH\!-\!CH\!=\!CH_2 \qquad\qquad CH_2\!=\!\underset{\underset{CH_3}{|}}{C}\!-\!CH\!=\!CH_2$$

$$(a) \qquad\qquad\qquad\qquad (b)$$

$$CH_2\!=\!CH\!\!\left\langle\bigcirc\right\rangle \qquad\qquad CH_2\!=\!CH\!-\!C\!\equiv\!N$$

$$(c) \qquad\qquad\qquad\qquad (d)$$
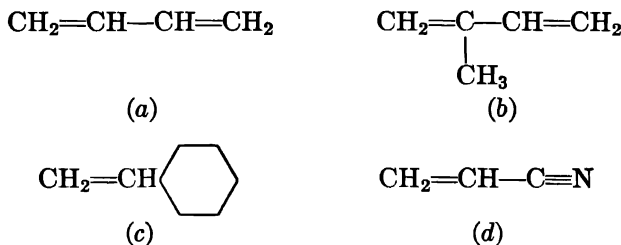
FIG. 9.16. Schematic structures for monomers used for synthetic rubbers. (a) Butadiene, (b) Isoprene, (c) Styrene, and (d) Acrylonitrile.

In "Butyl" rubber, the monomers consist of a major proportion of isobutylene, $CH_2\!=\!C(CH_3)_2$, and minor proportions of isoprene or butadiene. "Butyl" is superior to natural rubber in resistance to aging and in chemical resistance (this is explainable on the basis of its relatively low proportion of reactive double bonds). It has relatively low permeability for gases; therefore its use in automobile tire inner tubes.

"Neoprene" is a homopolymer of 2-chlorobutadiene,

$$CH_2\!=\!\underset{\underset{Cl}{|}}{C}\!-\!CH\!=\!CH_2$$
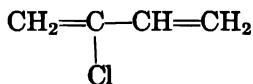
This elastomer, when properly compounded and vulcanized, has un-

usual resistance to oils and petroleum solvents, and better resistance to heat and light than natural rubber.

"Thiokol" rubbers are formed from organic halides and polysulfides by polycondensation, rather than by addition polymerization. An example is ethylene polysulfide, which has the structure

$$-CH_2CH_2-S_4-CH_2CH_2-S_4-CH_2CH_2-S_4-$$

Thiokol rubbers are vulcanizable by heat alone, and possess good solvent resistance, and good aging characteristics.

The Relation of Properties to Structure

The gross properties of solids are determined by the types of bonding which predominate.

(a) Ionic solids have high melting points and low coefficients of expansion. They form conducting ions when melted or dissolved. Mechanically they are hard and durable. Solubility and chemical properties vary over wide limits, depending upon the types of ions present and their arrangements.

(b) Atomic solids, that is, solids that form regular, extensive covalent networks, are also hard and high melting, have low coefficients of expansion and high densities. On melting, or when dissolved, simple molecules are formed rather than ions. With some of these solids—diamonds, for example—neither melting nor solution can be accomplished without some deep-seated chemical change being brought about simultaneously. Atomic solids are usually very resistant chemically.

(c) Molecular lattice solids, where the binding forces are chiefly van der Waals, are comparatively soft and of low mechanical strength, unless highly polymeric. They have low melting and boiling points, high coefficients of thermal expansion, and the melt or solution contains molecules.

9.26 THERMAL PROPERTIES

From the previous discussion it is apparent that thermal properties are determined by both gross and fine structural characteristics. Solids that form regular, predominantly ionic crystals (for example, ordinary inorganic salts and some silica minerals) have high melting points and low thermal conductivity, compared to metals. Melting is an abrupt physical transition. The latent heat of fusion is gen-

erally high, owing to the necessity of overcoming strong interionic forces.

Atomic solids, which form regular, indefinitely extensive, homopolar structures, also are exceptionally stable thermally: for example, diamond, graphite, silicon carbide, boron carbide, and aluminum nitride. These solids also have low thermal conductivity. In solids that can exist as supercooled liquids, the resultant randomness may lead to increased thermal resistance; e.g., fused silica, fused alumina, and many glasses and ceramics. Colloidal varieties of these and similar materials are accordingly sometimes used as thermal insulation.

Organic crystals, where the lattice energy is the result of weak van der Waals forces, are easily melted. Because of the low force fields surrounding individual molecules in the melt, the boiling points are correspondingly low. Among organic compounds of similar structures, the boiling point generally decreases as the symmetry of the molecule increases; the melting point, on the contrary, increases with increasing symmetry.

In most simple compounds, whether ionic, covalent, or metallic, these relations are sharply defined, reversible, and reproducible. This is no longer true for many complex structures. In most linear organic high polymers there is no sharp melting point, but rather a temperature range over which softening and flow occurs. This property is, of course, of practical utility in the extrusion and molding of thermoplastic resins. In thermoset resins, however, no appreciable softening or flow occurs below the point of thermal decomposition. Therefore, molding must be accomplished during a critical interval, when the reacting system concerned, still capable of flow, can be converted rapidly and irreversibly into its final infusible condition.

The specific character of these thermal patterns can frequently be varied within relatively wide limits by changes in the intimate structure of the materials concerned. For example, in polyamide resins ("Nylon") the melting point is lowered and the softness, flexibility, and solubility in certain solvents are increased as the dibasic acid component of the resin is varied from adipic acid, having 6 C atoms, to sebacic acid, which has 10 C atoms. The acrylic and methacrylic plastics become softer, lower melting, and more soluble as the length of the carbon chain of the alcohol used for esterification increases. In the silicones, similar phenomena are observed as the length and nature of the organic groups attached

to silicon are altered. The longer these organic groups are, and the more internal mobility they are capable of, the more the properties of the silicones depart from those inherent in the inorganic siloxane backbone structure. This backbone, present as a three-dimensional tetracoordinated structure in pure quartz, gives one extreme of properties. The manner in which these properties are altered by replacement of oxygen bridges by other metallic constituents in glasses has been mentioned. Further, more profound alterations occur when one of the four spatial bonds of silicon to oxygen is replaced (hypothetically) by the covalent bond of an organic radical, as in a monoalkyl silicone. These thermosetting resinous compounds are still rather hard, brittle, and high melting compared to most organic high polymers. The replacement of a second oxygen bridge by an organic radical results in a linear polymer, usually oily or rubbery in nature, and more organic than inorganic in its behavior. A third such hypothetical replacement gives a molecule with only one remaining Si—O bond, and incapable of polymerization; and the final replacement gives a tetraorgano substituted silane (SiR_4), a completely covalent molecule with properties not strikingly different from those of the analogous tetraorgano methane, CR_4.

9.27 MECHANICAL PROPERTIES

The following physical and mechanical characteristics are common to most ionic solids and to many symmetrical, close-packed covalent solids: (a) hardness of a relatively high order; (b) noncompressibility; (c) low distortion limits; (d) brittleness; (e) cleavage during fracture along fairly definite planes, related to crystallographic features or to grain boundaries; (f) elastic deformation, but within narrow limits; and (g) high yield values.

Deformation and Flow. In plastic materials, whether inorganic (glasses) or organic (high polymers), not only deformation, but also flow, is encountered when a stress is applied. This is because plastics may be considered, within broadly definable limits, to have the properties both of solids and of liquids.

In a true liquid the response to a shearing force is such that the shearing stress is proportional to the rate of shear or the velocity gradient. The yield value is zero. This represents simple or Newtonian flow. An ideal elastic solid, at the other extreme, obeys Hooke's law; i.e., the stress is directly proportional to the strain and is completely reversible.

Most plastic solids exhibit elastic deformation if the applied stress is below the yield value. Above the yield value, permanent deformation— that is to say, flow—occurs. In plastic flow, sometimes called Bingham flow, the deformation is proportional to the time of application of stress and is permanent. The transition from elastic to plastic behavior is usually not sharply defined.

Many liquids, emulsions, suspensions, and colloidal gels also exhibit marked departure from Newtonian flow. In these systems the rate of flow is likewise a function not only of the shearing stress, but also of time and the previous history of the sample In many systems of this sort (a bentonite-water gel is a good example) pseudo-Newtonian flow is exhibited above the yield point, but even this pattern is usually not entirely reversible. The "yield point" in such colloidal systems is generally associated with the overcoming of some type of physical "structure" (thixotropy). This phenomenon, which has been discussed previously, may be viewed as a disentanglement of discrete structures which, below the yield point, literally block one another's paths, and so inhibit flow.

Very dilute solutions of high polymeric organic substances sometimes exhibit true Newtonian flow. More concentrated solutions are always markedly nonNewtonian, and thixotropy is commonly encountered even at moderate concentrations. Presumably, both association of the chain molecules through van der Waals forces, and actual physical entanglement of the flexible chains are responsible for these effects.

Elasticity. Many thermoplastic high polymers are characterized by a high order of elastic extensibility. This behavior is presumably associated with the ability of such molecules to turn, bend, and uncoil around covalent bond centers. The multiplicity of such bonds in a chain molecule accounts for the remarkable flexibility and extensibility of many such materials.

In natural and synthetic rubbers, the reversible rotation, bending, coiling, and uncoiling of molecular chains around myriads of bond centers is realized to an exceptional degree. Elastic extensibility to the extent of 600 to 800 per cent is encountered. Above the elastic limit, of course, the ordinary laws of mechanics of rigid bodies apply. The stress-strain curve becomes steep and the break point is usually reached rapidly. X-ray examination indicates that the molecules of rubber and many synthetic elastomers undergo successively greater orientation on stretching. Fully stretched specimens frequently give highly crystalline diffraction patterns. This

may be looked upon as due to a "freezing" of the normally loose molecular structure, by physical means, into a regularly oriented, crystalline state. The process is physically analogous to solidification from the melt. Both processes evolve heat—the energy of crystallization of the system—and both lead from a random to an ordered state. Many organic high polymers having low elasticity, on the other hand, are partially crystalline in their normal, unstressed states. Examples are native cellulose, Nylon, and polyethylene.

Many plastics, on application of stress, undergo first a small, strictly elastic deformation; followed by a typical "creep" phenomenon, analogous to creep in metals. On removal of the stress, partial, instantaneous recovery takes place, followed by a slower, irregular recovery—again formally analogous to elasticity and anelasticity in creep recovery in metals. This behavior is, of course, evidence that both plastic and elastic effects occur simultaneously in the specimen.

Tensile Strength. Approximate values for the tensile strength and for Young's modulus of representative plastics and fibers at room temperature are listed in Table 9.5.

The tensile strength of a high polymer is affected by a number of factors, among which the following are of importance.

(1) The polar nature of the molecule. The more polar the chain molecules, the higher the cohesive forces, which are reflections of van der Waals and dipole interaction forces. Thus, a polar plastic-like cellulose is much stronger than a nonpolar material like polyisobutylene.*

(2) The average molecular weight. Most physical and mechanical properties of high polymers are additive; that is, they increase regularly with the chain length.

(3) The degree of orientation and crystallization. Most polymers are tougher when oriented. Good examples are Nylon and polyethylene terephthalate (Dacron or Mylar).

* Where hydrogen-containing polar groups, such as OH, NH_2, COOH, etc., are present on the polymer chain, "hydrogen bonding" plays an important role in determining the net attractive forces. The hydrogen bond is intermediate in strength between normal primary chemical bonds and ordinary secondary valence bonds. The hydrogen bond involves the interaction of the hydrogen on one molecule with a negative atom (usually oxygen) on a second or, not infrequently, on the same molecule.

Table 9.5 Approximate Mean Values of Tensile Strength and Modulus of Elasticity of Representative Plastics and Fibers at Room Temperature

Plastic	Tensile Strength, psi $\times 10^3$	Modulus, psi $\times 10^5$
Polyethylene	2– 3	0.1– 0.2
Polytetrafluoroethylene	2– 5	0.5– 0.7
Cellulose acetate butyrate	2– 7	0.7– 2.0
Cellulose acetate	2– 10	1.0– 3.5
Ethyl cellulose	2– 10	0.5– 5.0
Polyvinylidene chloride	4– 7	0.7– 2.0
Cellulose nitrate	3– 10	2.0– 4.0
Polystyrene	3– 10	1.7– 6.0
Polyvinylchloride-acetate	4– 8	3.5– 4.0
Polyvinyl butyral	4– 9	3.5– 4.0
Polyvinyl formal	9– 12	2.0– 3.0
Polymethyl methacrylate	6– 10	3.0– 5.0
Phenolformaldehyde (unfilled)	7– 8	7.5– 10.0
Nylon	8– 10	2.0– 3.5
Hard rubber	8– 10	2.0– 3.5
Glass-bonded mica	8– 13	70 –115
Viscose rayon	30– 45	8 – 15
Native cotton	40–125	8 – 16
Silk	45– 85	12 – 18
Nylon fiber	65–115	3 – 6
Glass fiber	200–210	70 – 90

(4) The extent to which close packing of chains can occur. This effect is highly pronounced in cellulose derivatives, where variations in strength with the degree of esterification or etherification can be correlated with this phenomenon.

(5) Plasticization. In general, plasticization decreases the tensile strength markedly, but increases the flexibility. This, of course, is the admitted function of the plasticizer. Plasticization is accomplished externally by addition of a compatible liquid or a second, flexible resin. It can also be accomplished internally by attachment of mobile groups at either regular or random positions along the polymer chain. Thus, "Butvar" is more flexible and less tough than "Formvar"; and a phenolic resin derived from octyl phenol ($HOC_6H_4C_8H_{17}$) is less brittle than one derived correspondingly from cresol ($HOC_6H_4CH_3$).

Cold Flow. Most solids are subject to "cold flow"—that is, occurrence of permanent set and relaxation, on long continued subjection to tensile or compression forces. This phenomenon, which **again**

bears considerable resemblance to "creep" in metals, is particularly pronounced with certain plastics. Cold flow can be observed either by holding a specimen under tension or compression at fixed displacement and observing the decrease in stress with time (relaxation), or by applying a constant load and observing the gradual increase of deformation with time (flow). In general, the creep relations will be found to be similar to those encountered in metals but to be many times greater in actual magnitude.

With most natural and synthetic rubbers, creep and relaxation are considerable even for fairly highly vulcanized varieties. The measurement of compression set of such elastomers is standard in control laboratories. Low "cold flow" may even be important at higher temperatures. Thus, in some applications of silicone rubber, where high compression stresses must be withstood, the extent to which permanent set occurs is important at temperatures far above those to which ordinary rubber can be submitted. "Cold flow" of such rubbers may therefore be measured at temperatures as high as 150–175 C.

"Cut through" is another manifestation of cold flow. In an electrical motor, where the windings may be under tension, cutting stresses may be applied to insulating components of the system. Resistance to such cutting forces and the ability to "relax" or undergo stress relief without rupture of the insulation is obviously important.

9.28 CHEMICAL PROPERTIES

Enough has been said previously to indicate that the chemical properties of a nonmetallic material are intimately related to its chemical structure and can frequently be predicted on that basis. For example, certain water-soluble ionic salts are useful as windows for optical measuring instruments, but such salts will certainly be subject to attack by a variety of chemical reagents. Among inorganic materials that are useful from a structural point of view are those massive minerals whose mechanical properties especially recommend them. However, where acid and alkali resistance is demanded, as in chemical stoneware, inert, refractory oxides or silicates in carefully selected combinations are required.

With organic materials, these relationships are more complex and more predictable. In general, the presence of "polar" substituents in an organic substance enhances its chemical reactivity. Thus, the unsubstituted hydrocarbons are more stable chemically than most of

their substitution products—such as the alcohols, aldehydes, ethers, halogen compounds, acids, esters, amines, etc. The presence of such polar groups also enhances water susceptibility. Thus, polyethylene, an unsubstituted hydrocarbon, is highly resistant to moisture. Polyvinyl alcohol, on the contrary, is readily attacked by water, as is polyvinyl acetate. Polyacrylic acid, a highly polar material, is practically impossible to separate from the water with which it is normally associated. On the other hand, the presence of a halogen in an organic polymer, as in polyvinyl chloride, polyvinylidene chloride, polytetrafluoroethylene, and polychlorotrifluoroethylene does not materially increase the water susceptibility.

The susceptibility of an organic molecule to oxidation (for example, by atmospheric oxygen or by specific chemical reagents) is also frequently predictable on the basis of structure. A good rule of thumb states that compounds that are already highly oxidized will resist further attack. Aromatic polynitro compounds are an example. Polymeric ketones and acids are others. On the other hand, the presence of unsaturated centers markedly increases oxidative sensitivity. Natural rubber, which has one double bond per chain unit, is more sensitive to oxidation than "Butyl" rubber, which contains only a small amount of unsaturation, or polyisobutylene, which contains essentially none.

Polysulfide resins, which contain sulfur in a low state of oxidation, are easily attacked by oxidizing agents, but have considerable moisture resistance. Polysulfones, on the contrary, are relatively resistant to oxidizing agents, but being more polar, are generally sensitive to hydrolysis.

Molecular-weight relations, geometry, orientation, and packing also markedly affect chemical resistance. Specialized textbooks should be consulted for details of these and similar relationships.

9.29   ELECTRICAL PROPERTIES

The possibility of interaction between electrical energy and matter stems from the fact that all matter is fundamentally a collection of electrons and positively charged atomic nuclei normally occupying equilibrium positions with respect to one another. A molecule in its normal state is neutral electrically only in the sense that there is an exact balance in magnitude between positive and negative charges. In a completely symmetrical molecule, the charges are also in geometric or spatial balance; that is, the center of gravity of negative charges coincides with that of positive charges. In a

stricter sense, this is exactly true only when the molecule is isolated from any disturbing electrical influence, such as an external field or a nearby second molecule. The monatomic rare gases come closest to electrical neutrality under normal conditions. Other symmetrical gases, at low pressures, also approximate to this condition. In general, however, the centers of gravity of positive and negative charges do not coincide. Electrically unbalanced molecules are said to contain permanent dipoles, and to have permanent dipole moments. The presence of unbalanced charges, whether resulting from permanent dipoles or induced by neighboring molecules, leads to the existence of stray force fields, already described as secondary valence forces.

The magnitude of a molecular dipole moment can be obtained from measurements of the dielectric constant, which can be looked upon as a measure of the ability of a substance to oppose an electric field, which it does either by linear displacement of electrons or by orientation of permanent dipoles.

It has already been suggested that the unique properties of metals are explained by the exceptional mobility of valence electrons. A loose definition of a "dielectric" is a substance which does not show metallic conduction.* Most organic substances and many nonsalt-like inorganic substances are therefore dielectrics.

When a nonconductor comes under the influence of an external field, the displacements which electrons undergo are defined mathematically by the Clausius-Mosotti equation:

$$P = \frac{\epsilon - 1}{\epsilon + 2} \cdot \frac{M}{d} = \frac{4}{3} \pi N \alpha_0$$

where P = the polarizability per mole of dielectric
ϵ = the dielectric constant
M = the molecular weight
d = the density
N = Avagadro's number = 6.06×10^{23}
α_0 = the ideal or intrinsic polarizability of the molecule

Polar and Nonpolar Molecules. Inherent in the Clausius-Mosotti expression is the assumption that a molecule has an electric moment induced in it by any external field. If the molecule is symmetrical, the moment disappears when the field is removed. Such molecules

* The consideration of semiconductors is left for subsequent chapters.

are nonpolar; for example, the rare gases (helium, argon, neon, etc.), symmetrical diatomic gases, such as hydrogen, nitrogen, and oxygen, and certain atomic lattice solids, such as diamond and silicon. However, most organic molecules and many inorganic molecules contain permanent electrical dipoles.* Such molecules, which possess permanent dipole moments, are called *polar molecules*. For polar molecules the expression for the polarizability contains a second term, as follows:

$$P = \frac{\epsilon - 1}{\epsilon + 2} \cdot \frac{M}{d} = \frac{4}{3} \pi N \left(\alpha_0 + \frac{\mu^2}{3kT} \right)$$

where μ = the permanent electric moment, k = the gas constant per molecule = 1.372×10^{-16}, and T = the absolute temperature in °K. α_0 is again the molecular polarizability due to an external field, and μ^2/kT is the molecular polarizability due to the internal charge displacement. The latter type of polarizability is temperature dependent; the former is temperature independent. If the dielectric constant is determined at a series of temperatures, the permanent dipole moment can be calculated, since the temperature-independent part then can be subtracted out.

Polar molecules are too numerous to list or even to classify. A few common examples are the hydrogen halides (HF, HCl, HBr, and HI), water (H_2O), carbon monoxide (CO), unsymmetrical halogenated methanes, such as $CHCl_3$, CH_3Cl, CH_3Br, CH_3I, $CHBr_3$, etc.

Since the moment of a homopolar molecule may be considered to be the vector sum of all the individual bond moments,† it is often possible to calculate the dipole moment of a molecule from its molecular structure. The values for the bond moments must of course first be known from the study of other molecules.

A diatomic molecule can be completely nonpolar only when the two atoms are identical; otherwise the centers of opposite charge will not coincide; as in CO, HCl, and ICl, all of which are polar. Triatomic molecules of the general structure B-A-B are nonpolar only in the rare case where their atoms lie on a straight line with

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* It may be helpful to think of the dipoles as internal charge displacements, similar to an electrical doublet.

† A bond moment is the electrical moment resulting from the union of 2 dissimilar atoms or groups, and is considered to be a property of the particular bond, more or less independent of other bonds present in the molecule.

the 2 B-A distances equal (e.g., CO_2, which may be written $O \leftarrow C \rightarrow O$). More complex molecules are nonpolar only when special structural effects operate so as to cancel out all bond moments. In tetramethylmethane, $(CH_3)_4C$, the 4 methyl groups are located at tetrahedral angles about the central carbon atom, and the C—H moments accordingly all cancel out vectorially. Similarly, carbon tetrachloride, CCl_4, has zero moment because the 4 tetrahedrally arranged C—Cl moments exactly cancel. Benzene (C_6H_6) is nonpolar because it exists as a plane hexagonal ring with a center of symmetry. The 6 C—H bond moments again cancel one another. On replacing 1 H atom in benzene with any other atom or group, such as in C_6H_5Cl, C_6H_5OH, $C_6H_5NO_2$, or even in C_6H_5D (where D = deuterium, the hydrogen isotope of mass 2) the molecule acquires a permanent moment whose magnitude varies with the nature of the group introduced. The normal, straight chain, paraffin hydrocarbons, $CH_3(CH_2)_nCH_3$, usually have zero moment. The vector cancellation of dipoles is illustrated in Fig. 9.17 for
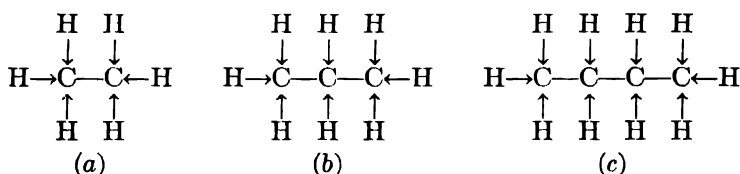
FIG. 9.17. Schematic representation of vector cancellation of dipoles in (a) Ethane, (b) Propane, and (c) n-Butane.

ethane, propane, and n-butane. At sufficiently low temperatures, many solids consisting of dipolar molecules show nearly zero moments, because the dipoles are "frozen"; i.e., they cannot rotate fast enough to be affected by a field of ordinary magnitude.

Ionic crystals, which are clearly polar, show correspondingly high polarizabilities, and when melted frequently become conducting.

It can be shown that forces due to primary chemical bonds, whether ionic or covalent, act only over very short distances, usually of the order of magnitude of atomic diameters (1–2 A). Van der Waals forces also are effective over relatively short distances (ca. 4–5 A). The forces which result from dipole-dipole interaction are of relatively longer range. One result of this is that the total energy of such a system, at a given temperature, may depend upon its shape, as well as its intimate molecular structure.

The magnitudes of ordinary molecular dipole moments are of the

order of 10^{-18} c.g.s. units, corresponding to one electrostatic unit of charge displaced by 1 A of distance—$10^{-10} \times 10^{-8} = 10^{-18}$ e.s.u. $\times$ cm = 1 Debye unit.

Dipole Moment and Chemical Structure. The measurement of dipole moment provides a method for determining the structure of many molecules. As an example it was early realized that the water molecule cannot be linear (H—O—H) but must rather be triangular $\left({}^{H}\diagdown_O\diagup^{H} \right)$ because of its high dipole moment. Measurements of dipole moments have also furnished clues as to the space relations of "geometric isomers." For example in dichloroethylene, $C_2H_2Cl_2$, there are two isomers, which are formulated as illustrated in Fig. 9.18. *Cis*dichloroethylene has a moment of 1.9
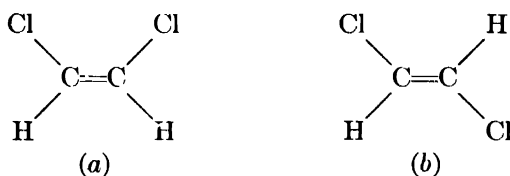
FIG. 9 18. Schematic representation of isomers in dichloroethylene, $C_2H_2Cl_2$. (*a*) Cis-dichloroethylene, which has a moment of 1.9 Debye units; and (*b*) Trans-dichloroethylene, which has zero moment.

Debye units, whereas the *trans*isomer has zero moment, since the two C—Cl and the two C—H dipoles exactly cancel one another. In disubstituted benzene derivatives, the magnitude of the moment is determined by the location of the two substituents. A good example is furnished by the three isomeric dichlorobenzenes, Fig. 9.19.
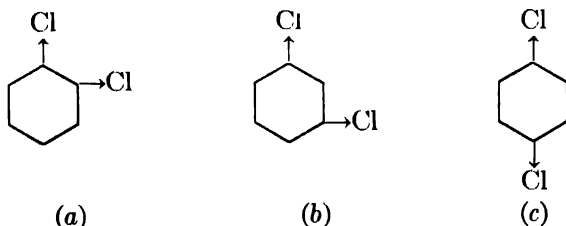
FIG. 9.19. Three isomeric dichlorobenzenes. (*a*) Ortho-dichlorobenzene, $\mu = 2.25$ Debye units. (*b*) Meta-dichlorobenzene, $\mu = 1.48$ Debye units. (*c*) Para-dichlorobenzene, $\mu = 0$ Debye units.

In the para derivative, the two C—Cl dipoles, being exactly 180° out of phase, precisely cancel one another.

Mechanism of Conduction in a Dielectric. It will now be useful to inquire briefly into the behavior of a neutral molecule subject to an external electrical field. It is well known that a substance that is an insulator towards a d-c field may show an appreciable a-c conductivity, when a periodic polarization, i.e., displacement of electrons in phase with the applied voltage, is possible. Nonpolar molecules, as has been indicated, are not readily polarized under a-c. Polarization is much more pronounced for molecules that possess relatively large permanent dipoles. Here the molecules are readily oriented or partially oriented parallel to the a-c field. If the frequency of the alternating field and the viscosity of the medium are both low, molecular oscillations that occur in phase with the field give rise to an alternating current.

If a d-c field is applied to a randomly oriented polar dielectric, the dipoles are oriented by the field, and, at moderate field strengths, will maintain this orientation indefinitely. If the field is removed, the kinetic energy of the molecules will soon completely destroy the imposed orientation. The time required for the orientation achieved under steady d-c to fall to $1/e$th of this value (where e is the base of natural logarithms) is the "relaxation time," a quantity that varies with the nature of the molecule, with the viscosity of the medium, and with the inverse of the absolute temperature. At low a-c frequencies, it is also reasonable to assume that complete relaxation may occur between pulses. At high frequencies, however, orientation cannot keep up with field oscillations; and at very high frequencies, the dipoles are not able to follow the field at all. The dielectric constant measured under these conditions corresponds to the temperature independent part only—that is, to that part which is owing to electronic polarization alone.

When a dielectric comes under the influence of an a-c field, where the current ideally lags by 90° behind the voltage, the actual phase angle is less than 90° by an amount equal to the so-called loss angle. The in-phase component produces heat and consumes power in relation to the loss angle Δ. At ordinary frequencies the expression $\tan \Delta = \epsilon''/\epsilon'$ applies, where ϵ' is the dielectric constant, and ϵ'' is the dielectric loss factor.

Starting with the above familiar picture, dielectric theory is able to predict, with considerable accuracy, the electrical properties of relatively simple liquids. However, for polar organic high polymers the maximum dielectric loss factor is much lower than simple theory demands, and occurs at much lower frequencies than for

simple polar liquids. The dielectric constant is also frequently much higher. These effects are, in the first approximation, owing to the interactions of multiple dipoles located along the linear chains of these very large molecules. In most high polymers, the chains are twisted and folded, more or less at random, into complex configurations. The individual dipoles must accordingly relax, when under electrical stress, through rotation and uncoiling of these complicated chain segments. In a sense, then, the polymer behaves as a mixture of different molecules, each with its own relaxation time, each corresponding to one of the many possible configurations that the linear or cross-linked macromolecule can assume. The relatively higher dielectric constant of polar polymers can then be explained by the assumption that only where the appropriate chain segments happen to line up properly through chance molecular motion can the individual dipoles pair off, and thus decrease the net response to the field, as occurs easily with simple liquids.

From the explanation given above, it is apparent that the best electrical insulators are those materials that are the least polar. For example, among the lowest power-factor materials for use in liquid-filled transformers are hydrocarbon oils. In gas-filled transformers, certain stable, symmetrical compounds are found to be the most desirable. Among organic high polymers which are useful as insulation, hydrocarbons again show the lowest electrical losses; e.g., polyethylene, polystyrene, polybutene, and some synthetic rubbers.

Changes in the chemical structure of an inorganic glass or of an organic high polymer can often be correlated with changes in electrical properties, such as polarizability, relaxation time, and dielectric loss factor. Alterations in electrical relaxation time often go hand in hand with changes in mechanical relaxation time and in flexibility. When polyethylene is chlorinated, for example, the flexible highly crystalline hydrocarbon changes gradually to an amorphous, rubbery state, then to a leathery substance, and finally, at about 60 per cent total chlorine, to a brittle solid. Simultaneously, the loss factor, tan Δ, increases, reaches a maximum, and then decreases again. The shape of the tan Δ vs. frequency curves indicates an increase in dipole orientation relaxation time, which runs parallel with an increase in the brittle temperature.

Dielectric Strength. It is common to classify insulating materials according to their dielectric strength. This characteristic is simply defined as the a-c (or in some cases, d-c) voltage that can be applied to the material before puncture or dielectric breakdown occurs.

The dielectric strength varies with the thickness of the specimen, the size and shape of the electrodes used, and the conditions of the test. As practically determined, this property is not subject to greatly accurate reproducibility, yet it is a very important means of testing the suitability of a material for an intended electrical application.

In Table 9.6, some average electrical properties are listed for a

Table 9.6 Electrical Properties of Polymers

Polymer	Volume Resistivty, 50% Relative Humidity	Dielectric Strength Step by Step, $\frac{1}{8}$ in.	Dielectric Constant			Power Factor		
			60~	10^3~	10^6~	60~	10^3~	10^6~
Polystyrene	10^{17}–10^{19}	500	2.4–2.7	2.4–2.7	2.4–2.7	0.0002	0.0002	0.0002
Polytetrafluoroethylene	10^{16}	400	2.0	2.0	2.0	0.0001	0.0001	0.0001
Polyethylene	>10^{13}	400	2.3	2.3	2.3	0.0004	0.0004	0.0004
Natural rubber	10^{13}–10^{16}	500	3.0	3.0	3.0	0.006	0.004	0.06
Glass-mica	10^{15}	450	7–8	7–8	7–8	0.004	0.003	0.002
Polyvinyl carbazole	10^{15}–10^{16}	800	3.0	3.0	3.0	0.0015	0.0007	0.0007
Polyvinyl butyral	>10^{14}	400	3.6	3.6	3.3	0.007	0.007	0.009
Polyvinyl formal	>10^{14}	400	3.6–3.7	3.3	3.0	0.007	0.01	0.02
Butyl rubber	10^{14}–10^{16}	600	2.9	2.8	2.8	0.01	0.015	0.02
Shellac compounds	10^9–10^{10}	400	2–4	3–4	4–5	0.01	0.01	0.03
Ethyl cellulose	10^{12}–10^{14}	400	2.5–4	3–4	3–4	0.01	0.01	0.04
Silicone rubber	10^{10}–10^{11}	350	2.5–4	2.5–4	2.5–4	0.015	0.01	0.02
Cellulose acetate	10^{10}–10^{13}	250	5.5–6	5–6	4–5.5	0.02	0.03	0.05
Nylon	10^{13}–10^{14}	400	4–5	4–5	3–4	0.014	0.02	0.04
Polymethyl methacrylate	10^{14}	350	3.5–4.5	3–3.5	2.7–3.2	0.05	0.04	0.03
Phenol formaldehyde, filled	10^{11}–10^{12}	300	5–6	5–6	4.5–5	0.08	0.05	0.02
Polyvinyl chloride, plasticised	10^{11}–10^{13}	350	5–6	4–6	3–4	0.12	0.10	0.10

number of high polymers commonly used as electrical insulation. It is to be emphasized that the values given represent, in general, observed ranges and are not to be construed as representing precisely the properties of any particular specimen.

9.30 CONCLUSION

It has been necessary, in the course of this chapter, to touch upon a large number of subjects and to make brief excursions into a number of related fields of chemistry and physics. The field of nonmetallic materials is much too broad to be treated otherwise. However, the coverage of any single aspect of this difficult subject has been necessarily sketchy, and possibly elementary at times. For details on many of the problems encountered it will frequently be desirable to consult the specialized literature. A large number of these problems are not only of great academic interest, but they are also of considerable practical significance to many industrial operations.

In subsequent chapters, some of the materials and processes dis-

cussed theoretically in the present chapter will be treated in more detail from a point of view much closer to that of the operations engineer.

Review Questions

1. Name ten inorganic materials and ten organic materials and indicate whether each is of natural or synthetic origin.

2. List the three fundamental types of chemical bonds and indicate which is the dominant mechanism for an inorganic crystal, for a diatomic gas molecule, for intermolecular bonding of liquids or crystalline solids, and for most organic materials.

3. What is an amorphous material?

4. Describe the property known as thixotropy.

5. What is polymerization? Name the three steps involved in this process.

6 How does copolymerization differ from polymerization?

7 Describe the properties typical of thermoplastic resins. How do properties of thermosetting resins differ?

8. What materials exhibit flow under load?

9. How do melting and softening of materials relate, generally speaking, to the structural bond present?

10. What is a polar molecule? How does its polarizability differ from that of a nonpolar molecule?

10 ELECTRICAL INSULATION

by A. J. SHERBURNE * and K. N. MATHES †

10.1 INTRODUCTION

The great variety of materials available today sometimes seems only to add difficulty to the engineer's problems of selection. To those unfamiliar with the field, this seems particularly true with respect to electrical insulation.

In Edison's day the insulation problem was quite the opposite. The first underground voltage distribution system used with Edison's incandescent light failed successively as wood, coal tar, and a composition of powdered slate were tried with wrappings of muslin. Success came only after extensive study by Wilson S. Howell, of the Edison staff, showed that a "cooked" substance of refined Trinidad asphaltum, mixed with oxidized linseed oil, paraffin, and beeswax, was satisfactory as an insulating compound.

As engineering requirements for specific properties have developed and broadened, many new insulating materials have appeared, until today the field has become highly specialized and very important. This chapter includes a classification of the present insulation materials based on allowable operating temperatures. Typical applications are given to show how the materials are combined and applied to produce insulations for electrical apparatus.

Properties

10.2 PROPERTIES REQUIRED

Electrical insulating materials are defined as materials which offer a very large resistance to flow of current, and for that reason they are

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used to keep the current in its proper path along the conductor. The primary purpose of insulation is therefore electrical, and in the early days of the electrical industry this was the only purpose. As service requirements have broadened, insulation has gradually assumed a thermal, mechanical, and even chemical burden as well. Often properties to meet such secondary requirements are so necessary that they, rather than the electrical properties, limit the choice of material. For example, heat resistance is essential in heating devices; resistance to aging under heat is required in power apparatus; arc resistance in switchgear and control apparatus; high mechanical strength in rotating machinery; toughness to resist shock as in equipment for naval applications; flexibility for insulation on wire and cables; chemical stability in severe atmospheric conditions; and appearance as required in appliances.

Thorough consideration of operating conditions will go far toward solving an insulation problem. Nevertheless, manufacturing methods can nullify the best materials. Proper care must be taken not to injure the insulation by tearing, abrasion, scorching, etc. Experience or application tests must be the engineer's guide in selection of an insulating process. Tests of this kind, demonstrating the influence of methods and processes on insulation, are often as important as the properties of the material selected. This should be kept in mind throughout the following discussion of properties.

For convenience, the various properties are grouped as electrical, thermal, mechanical, and chemical.

10.3 ELECTRICAL PROPERTIES

The selection of an insulation often depends on the relative importance of insulation resistance, surface conductivity, power factor, dielectric constant, dielectric strength, and arc resistance. They are the electrical properties of an insulating material that are discussed in the following paragraphs.

Insulation Resistance. Insulating materials serve to separate conductors at different electrical potential. Often it is only necessary that the insulation prevent a large flow of current between the conductors (see dielectric strength). However, in some types of equipment in which relatively high impedance circuits are used (electronic, control, etc.) it may be necessary, for proper operation, to maintain high values of resistance over and through the insulation between conductors.

The value of the d-c resistance between the conductors is known as the *insulation resistance* for the particular geometry of insulation involved. Since both geometry and the properties of the material determine insulation resistance, it is usual when considering insulating materials to determine surface and volume resistivity. *Surface resistivity* can be described as the resistance between two opposite edges of any square portion of the insulation surface; and *volume resistivity* is the resistance between any two opposite faces of a unit cube of the

☰ Laminate   ▨ or ⧅ Metal
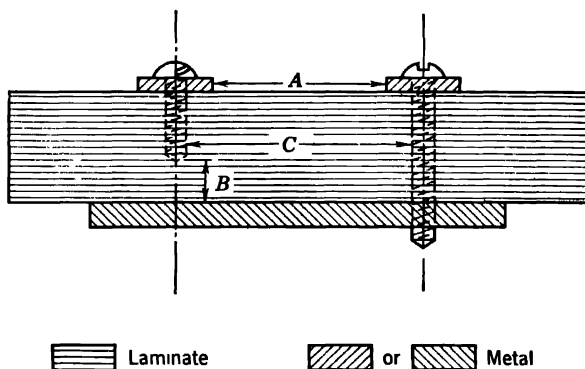
Fɪɢ. 10.1. Schematic sketch of laminated insulation illustrating components of insulation resistance. (*A*) Surface resistance; (*B*) Volume resistance, perpendicular to lamination; (*C*) Volume resistance, parallel to lamination.

insulating material. Since insulating materials are often not homogeneous, the surface and volume resistance may have different values, depending upon the orientation of the voltage stress. The insulation resistance between the terminals mounted on a laminated insulating material, as shown in Fig. 10.1, depends on a combination of the surface resistivity, volume resistivity in the direction of the laminations, and the volume resistivity perpendicular to the laminations. The nature of the insulating material, temperature, and voltage stress, and the degree of exposure to atmospheric moisture and contamination are among the factors determining resistivity. Figure 10.2 shows the decrease in resistivity of a typical laminated insulating material during exposure at high humidity. The lowest resistivity is most important in determining insulation resistance. If an insulation configuration, such as is shown in Fig. 10.1, is exposed to high humidity, surface resistance decreases rapidly; ultimately, however, volume resistance attains a lower value. Consequently, first surface and then volume

resistance is the controlling factor determining insulation resistance.

Because insulation resistance is so affected by moisture and contaminants, it is often measured in an attempt to determine the condition of insulating materials in service. Such measurements provide some indirect indication of the likelihood of actual dielectric failure, but they need careful interpretation. They are most useful when determined repeatedly after increasing time intervals.
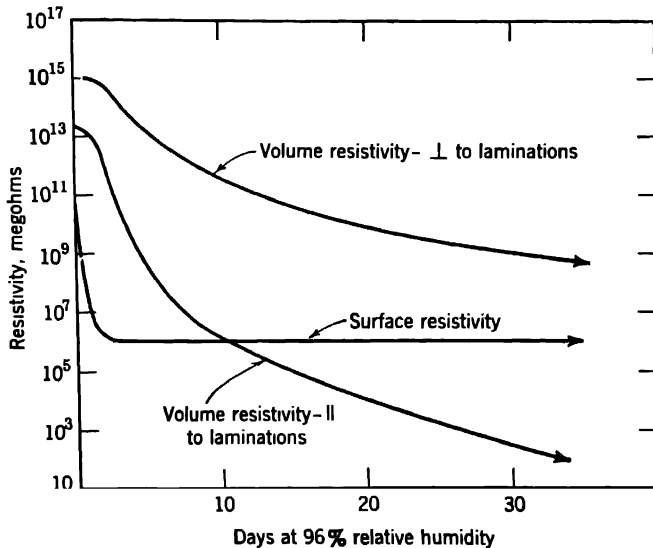
FIG. 10.2.   Resistivity versus exposure to high-humidity atmosphere for paper phenolic laminate.

Dielectric Strength. If the voltage across an insulating material is increased slowly, the way in which the current increases depends upon the nature and condition of the material as illustrated schematically in Fig. 10.3. For material A, the current increases very slowly and approximately linearly with voltage until a large, sharp increase results in what can be described as disruptive dielectric breakdown. In contrast, for material B the current increases more rapidly until current "runaway" occurs. It can be shown that the voltage at which current "runaway" occurs depends upon the rate at which the voltage is increased. It is customary, therefore, to define the rate at which the voltage is increased, so that a more definite, though arbitrary, value of dielectric breakdown may be obtained. It is also observed that with a relatively slow increase in voltage

material B may show a very marked increase in temperature, and the failure is then termed "thermal" breakdown.

Dielectric strength is defined as the potential gradient at which breakdown occurs. It is easily calculated for uniform fields by divid-
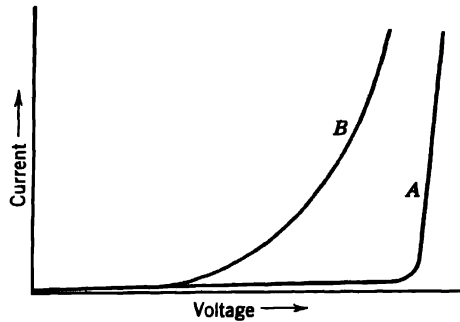
Fig. 10.3.   Current flow preceding insulation breakdown.   (A) Disruptive breakdown; (B) Thermal breakdown.

ing the breakdown voltage by insulation thickness. Nonuniform fields are common however, as indicated by a flux plot for a cable insulation, and the higher dielectric stress near its copper must be taken into account in actual design. The dielectric strength of an insulating material decreases with the length of time that voltage is applied, as shown in Fig. 10.4. Moisture, contamination, elevated
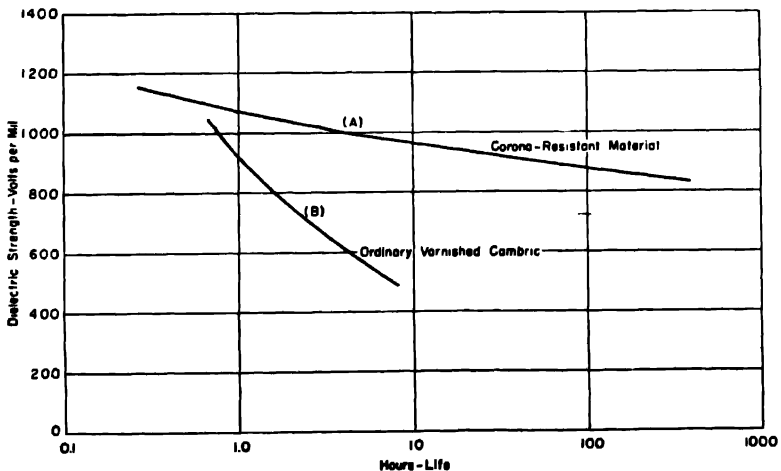
Fig. 10.4.   Life of insulation versus pulse voltage required to produce corona.

temperatures, heat aging, mechanical stress, and other factors may also markedly decrease the dielectric strength to as little as 10 per cent of the short time values at standard laboratory conditions. At radio frequencies the dielectric strength may also be considerably less than at 60 cycles. In addition, the variation on dielectric strength for an insulating material is usually considerable when compared, for example, to the tensile strength of steel as shown in Fig. 10.5.
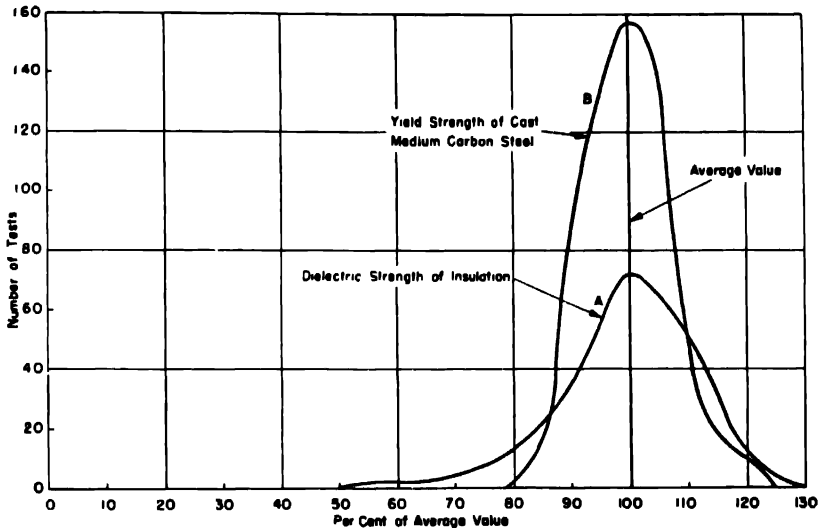
FIG. 10.5. Distribution curves of yield strength of cast steel and of dielectric strength of an insulation.

When the above factors are taken into account, it is apparent why the design value of voltage stress may be limited to 20 to 40 volts per mil when the average short-time dielectric strength may range from 1000 to 2000 volts per mil.

Dielectric failure that occurs along the interface between a solid insulating material and air, or a liquid insulating material, is termed "surface" breakdown. Allowable design values for voltage stress along a surface may be even lower than those allowed for the material itself, since effect of contamination and voltage-stress concentration may be even more important at the surface. Minimum creepage and clearance distances may also be needed to avoid chance shorting from external objects.

Despite the limitations discussed, the value of dielectric strength is useful in comparing insulating materials, determining the effect of

environmental and operating conditions, measuring uniformity, and controlling acceptance of material.

Power Factor and Dielectric Constant. When insulating materials are used at high frequencies, the power loss in the material itself may
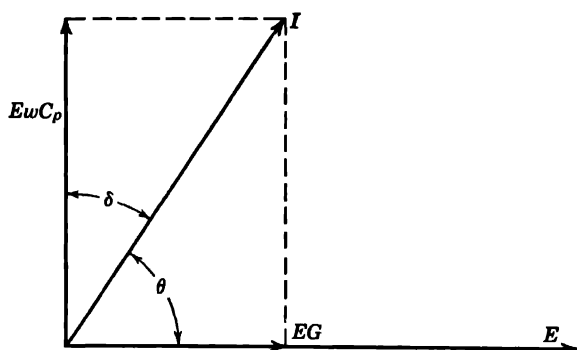
Fig. 10.6. Vector diagram—equivalent parallel dielectric circuit.

be very important. An insulating material can be represented as a combination of resistance and "pure" capacitance in parallel. The vector diagram for this equivalent parallel circuit is shown in Fig. 10.6. The energy loss in the dielectric is given by the following equation:

$$\text{Energy per unit volume} = E^2 f \tan \delta \epsilon'$$

E = voltage

f = frequency-cycles per second

$\tan \delta = \dfrac{1}{2fC_p} R_p$ = tangent "loss angle" dissipation factor

$\epsilon' = \dfrac{C_p}{C_a}$ = dielectric constant inductive specific capacitance

C_p = equivalent parallel capacitance

C_a = a capacitance similar in geometry to that for C_p, in which the dielectric is replaced by vacuum

R_p = equivalent parallel resistance

$\sin \delta = \cos \theta$ = power factor

$\epsilon' \tan \delta$ = loss factor

Although the *dissipation factor* is more useful, *power factor* is often given instead, probably because of its use in somewhat different fashion in conventional power circuits. Below values of 0.1, the dissipation factor and the power factor are nearly equivalent. The power factor depends mainly upon the nature of the material, tem-

perature, moisture exposure, voltage, and particularly on frequency.

The *dielectric constant* is a measure of the electrostatic energy stored in the insulating material per unit volume under per unit of voltage gradient. It is dependent also on temperature, moisture exposure, frequency, and other factors. For design purposes it is particularly important that both power factor and dielectric constant should be determined for the conditions involved in the expected application.

Power factor and dielectric constant at power frequencies can be used to compare insulating materials and determine the effect of environment and operating conditions. When measured at high voltages, power factor and dielectric constant are useful in evaluating high-voltage insulation systems. Dielectric constant measurements are also useful in the consideration of insulating materials used in series, since the voltage across each material will bear an inverse relationship to the dielectric constant.

10.4 THERMAL PROPERTIES

Insulation breakdowns are most frequently the result of heat and moisture. Heating causes chemical changes in the insulation which are aggravated by the presence of moisture. It is for this reason that the thermal properties are second only to electrical properties in importance for the average application. Heat aging, thermal conductivity, thermoplasticity, thermal expansion and contraction, and inflammability are the thermal properties that must be considered. Brittleness at very low temperatures is also of importance, since materials which become brittle at these temperatures tend to crack when under mechanical stress.

Heat Aging. Aging is, in effect, the wearing out of an insulating material by reducing its resistance to mechanical injury. It increases rapidly with temperature, approximately doubling for each increase of 10 C to 16 C, depending upon the material. Such increases in temperature cause dehydration of all cellulose materials and an intensification of oxidation and other chemical changes in both cellulose and varnish substances. These are the effects that lead to brittleness, cracking, shrinking, and, under vibration and stress, ultimate crumbling and disintegration (see Fig. 10.7). Electrically, the material does not wear out until electrical breakdown occurs; thus, aging may progress quite far before a mechanical movement breaks the brittle insulation sufficiently for voltage puncture.

The standard test for heat aging has been a flexibility test preceded by aging in an oven at elevated temperature. For example, this test for varnish may consist in aging a varnish-on-metal film at 105 C until a bend around a $\frac{1}{8}$-in. mandrel cracks the film. Flexibility, however, is not usually the determining factor in the actual life of a varnish in a winding or coil. In one such comparison two identical
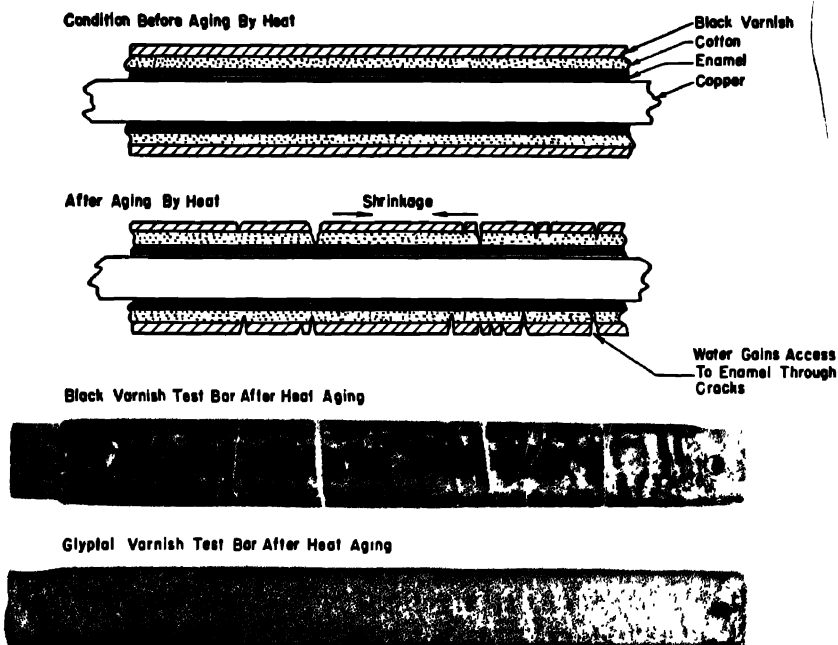
Fig. 10.7. The effect of heat aging on varnish insulation.

bars were covered, one with black oil-base varnish insulation and the other with a newer Glyptal varnish insulation (Fig. 10.7). In the flexibility aging test the black varnish proved best. However, after the bars were heated at 150 C for a period of several weeks and not flexed, shrinkage and oxidation caused severe cracking of the originally flexible black oil-base varnish, whereas the heat seemed only to toughen the Glyptal coat. Thus, the flexibility aging test, although it may be useful in measuring the integrity of a finish coat under exposure to air and heat, has little value for a coil or motor-winding application without the confirming evidence from the other test.

Thermal Conductivity. Insulating materials must often serve as heat conductors. The internal temperature of a winding depends upon the rate at which heat can escape through the insulation to the surroundings, and therefore a well-bonded, compact coil is better than one having porous, air-filled insulation of low over-all thermal conductivity.

Thermal Plasticity. Pressure on the wires of a wound coil varies under operating conditions because of the expansion and contraction of the parts caused by variations in temperature. Although, in practice, pressure generally is accompanied by slight vibratory motion and consequent abrasion, it is valuable to observe the flow of wire insulation at high temperatures in the absence of vibration. For this purpose, a device is used that subjects a crossed-wire sample to pressure at elevated temperature while 125-volt direct current is applied. The material under test insulates the wires, and proper care is taken to prevent grounding or shorting elsewhere. The results of this test are indicative of the resistance of the material to failure caused by pressure or flow of film. Actually, since a high degree of thermoplasticity may be unimportant in many applications or even of considerable benefit, it should not always be viewed with disfavor.

Thermal Expansion and Contraction. Where an insulation will be subjected to wide temperature variation, the thermal expansion and contraction characteristics of a material may be the limiting factors in selection. Temperature variations will usually be low enough to make these properties unimportant except when using filling compounds, large masses of material, or brittle materials. Some types of apparatus require precision in the placement of various elements and, with these, thermal expansion of insulating materials may be very important.

10.5 MECHANICAL PROPERTIES

Insulations are regularly tested for impact strength, tensile strength, hardness, toughness, elongation, flexibility, adhesion, and abrasion resistance. In addition, there are certain other mechanical properties uniquely important to varnish products. These are bonding, penetration, and through-curing.

Bonding. Bonding is the degree to which a compound binds insulating material and wires into a solid mass. In rotating armatures, considerable stress on insulating materials is caused by centrifugal force. The insulating material should not deform plastically and

break the bond of wire to wire under such treatment. Furthermore, heat from the windings must be dissipated through the insulation to the surroundings. Thus, bonding serves two functions; it binds the conductors together, thus minimizing movement and consequent abrasion, and it also improves the heat conductivity of the conductor mass. Bonding strength is typically listed as high, medium, or low.

Penetration and Filling. Penetration is the degree to which a compound will permeate its supporting structure and it may be recognized as a generalized function of viscosity, surface tension, and the ability to wet the structure. Filling is related to the ability of a compound to produce a void-free structure.

Through-Curing. Through-curing is the ability of a material such as varnish to harden through a mass. Complete hardening, or *curing*, as it is traditionally called, is most difficult with an oxidizing varnish, because oxidation is at a minimum inside a coil and diffusion of oxygen inward is very slow. Varnishes that require little or no oxygen for through-curing thus become of importance where curing through a mass is necessary. Material specifications describe this property in terms of fast, slow, and noncuring.

10.6 CHEMICAL PROPERTIES

The resistivity of an electrical insulation to deleterious action by water, oil, ozone, corrosive vapors, acids, alkalies, and certain other chemicals is a major factor affecting insulation life under the wide variety of uses in the chemical, paper, petroleum, and metals industries.

Effect of Water and Tropical Tests. Water directly lowers electrical properties, such as electrical resistance and dielectric strength. The water may be transmitted through an outside coating and cause damage inside; it may be directly absorbed by an insulating material; it may cause a chemical change of the insulation itself; or it may drastically lower the surface resistance of an insulator.

Water will pass less than half as fast through a film made with the newer phenolic-oil type of varnishes than it will pass through the old type of varnishes. No varnish, enamel, lacquer, or paint film is 100 per cent water impervious, however, and moisture resistance and water repellence depend a great deal upon the degree of cure of the film, and upon the character of the film-supporting material. The most absorbent supporting materials are cotton, paper, and asbestos, the water being soaked up by wick action of the fibers. Under moist

conditions or high humidity these materials should be avoided if possible.

The effect of water absorption on electrical properties may be determined by measuring dielectric strength, insulation resistance, or power factor after immersion in water or during exposure at high humidity.

Acid and Alkali Resistance. Resistance to weak acids and alkalies is tested by submerging coated test samples (strips or rods) in an acid or alkali solution and measuring the leakage current and time required before complete failure occurs.

Oil Resistance. A difference should be noted between oilproofness and oil resistance. *Oilproof* materials are those that are unattacked by oil, whereas *oil-resistant* materials are those that protect against oil though they may become soft.

General. Any insulating material that is likely to come in contact with ozone, corrosive vapors, or special chemicals should be thoroughly tested under exposure to these substances before assurance can be had that the material will perform satisfactorily as an electrical insulation.

Classifications

10.7   TEMPERATURE CLASSIFICATION

The materials ordinarily employed in insulations include cotton, silk, paper, rubber, wax, resins, asphalts, compounds, natural-resin varnishes, synthetic-resin varnishes, plastics, mica, glass, asbestos, porcelain, and pure oxides which are used as solids; the dielectric liquids, petroleum oils and synthetic oils; and the dielectric gases, hydrogen, dichlorodifluoromethane (a gas used as a refrigerant), nitrogen, and air, which is perhaps the most important of the gases. This classification according to state, though undoubtedly the most obvious classification, is of little informative value and might easily cause misunderstanding. Several of the insulations, for example, are applied in the liquid state but serve as insulation in the solid state.

Recognition of the potential danger of heat to insulation is given in the AIEE standards, in which the insulating materials used in the dry or finished state as solids are classed according to their permissible operating temperatures. These classifications are defined in Table 10.1. The limiting temperature is supposed to be at the hottest point, and, for coils, is arbitrarily taken as 15 C higher than the out-

Table 10.1   AIEE Classifications of Electrical Insulation *

Class		Assigned Limiting Insulating Temperature
O	Class O insulation consists of cotton, silk, paper, and similar organic materials when neither impregnated nor immersed in a liquid dielectric.	90 C
A	Class A insulation consists of: (1) cotton, silk, paper, and similar organic materials when either impregnated or immersed in a liquid dielectric; (2) molded and laminated materials with cellulose filler, phenolic resins, and other resins of similar properties; (3) films and sheets of cellulose acetate and other cellulose derivatives of similar properties; and (4) varnishes (enamel) as applied to conductors.	105 C
B	Class B insulation consists of mica, asbestos, fiber glass, and other inorganic materials in built-up form with organic binding substances. (A small proportion of Class A materials may be used in Class B applications for structural purposes only.)	130 C
C	Class C insulation consists of mica, porcelain, glass, quartz, and similar inorganic materials not used in construction with a material from the other classes.	No limit selected
H	Class H (approved but not yet adopted) consists of (1) mica, asbestos, fiber glass and similar materials in built-up form, with binding substances composed of silicone compounds or materials with equivalent properties; (2) silicone compounds, not rubbery or resinous in form, or materials with equivalent properties. A minute proportion of Class A material may be allowed only where essential for structural purposes during manufacture. The electrical and mechanical properties must not be impaired by the application of the temperature permitted for Class H materials. (The word "impaired" is here used in the sense of causing any change which would disqualify the insulating material for continuous service.)	180 C

* For a worth-while and detailed discussion of this classification and other insulation standards, the reader is referred to *AIEE Standards No. 1*.

side surface. Thus, a Class O material may be used in a coil that is to operate with a surface temperature of 75 C. It follows that with the limiting ambient temperature of 40 C, a surface-temperature rise of 35 C is permissible, or a winding-temperature rise of 50 C can be allowed.

These standards have become conservative with the advent of the newer synthetic insulations.* Often it is possible to use coils at somewhat higher temperatures and still have what may be considered adequate service, as long as cellulose materials such as paper and cloth are prevented from dehydration and oxidation, by a good varnish film. There have been instances, for example, when coils, insulated with cotton and treated with synthetic resin varnish, have withstood peak temperatures as high as 300 C for a very short time without serious injury, whereas cotton or paper would have been entirely burned at a much lower temperature.

Oils and gases are not included in the foregoing AIEE classification. They will be grouped separately.

Insulating Materials

10.8 GENERAL

Electrical insulating materials are used for wire coating and cable construction, for insulating spacers and structural purposes, and for coil, generator, and motor-winding applications. For convenience they are grouped as (a) dielectric solids, (b) dielectric liquids, and (c) dielectric gases.

10.9 SOLID DIELECTRICS

(1) *Untreated Cotton.* Untreated cotton is used principally in the form of cloth or tape. It is flexible in this form, capable of close wrapping, possesses good mechanical strength, and readily absorbs insulating varnishes and compounds. When used for covering wire, either as a single or double covering, it requires relatively little space, and at the same time provides mechanical protection during coil winding and acts as a base to which varnish may be applied to help bonding of turns.

(2) *Silk Cloths and Tapes.* Because of high dielectric and mechanical strength, silk cloths and tapes are used where small thickness or low space factor is important, as in meters and instruments. Rayon tapes and woven cellulose acetate tapes (Class *A*) are replacing silk for many applications.

(3) *Untreated Paper.* Untreated paper, applied in a special wrapping of thin tape, is used as a spacer between layers of certain types

* At this time (1953) there is international activity towards addition of intermediate classes to cover the vast number of synthetic resin products which can be used at service temperatures between *A* and *B* and *B* and *H*.

of control coils and transformer windings and as an insulation for high-voltage cables. Fibers and pressboards are used in sheet and tape form for wrapping conductors, for separators, slot armor, etc., and to provide a mechanical protection and backing for other insulation.

(4) *Rubber.* Rubber has been used largely for cable and lead wires, but with improvements in rubberlike synthetics (see Chapter 12) and their methods of application, the use of rubber as an insulation may gradually disappear. Rubber is damaged by heat, ozone, and oil, but it has good abrasion and water resistance.

(5) *Waxes.* Waxes, because of their high electrical resistance and exceptional water repellence, have been used as impregnating compounds in condensers and high tension coils of various kinds. The commonest wax is paraffin, which has a dielectric constant of 2; chlorinated naphthalenes have a dielectric constant of 6.

10.10   NATURAL RESIN VARNISH

One of the most important classes of substances, from the point of view of life and dependability of electrical apparatus, is the insulating varnishes. They are manufactured from suitably prepared vegetable and animal oils, natural gums or resins, synthetic resins and pitches, or asphalts, thinned to a proper working consistency with solvents. Usually they are classed as clear or black varnishes. The clear types now include a wide range of different natural varnishes (oleo-resinous types) and oil-modified-synthetic resin varnishes. The black are asphaltic-base materials (oleo-asphaltic types). Varnishes are also classed as to their drying properties and uses; e.g., air-drying, quick-baking, and plastic properties, finishing, impregnating, etc., uses.

The correct terminology for paints and varnishes is graphically illustrated in Fig. 10.8. One outstanding exception to those definitions should be noted: Varnishes used for coating wire and sheet iron or steel are usually called *enamels,* although they normally contain no pigment.

Natural Resins. The natural resins, or "gums," include shellac, rosin, Kauri, Manila, Congo copal, and many others, most of which are found in India or the East Indies. They are gums or pitches that exude from trees, or bugs (for shellac), or from fossil accumulations that come from fossilized trees. Shellacs and copals, especially, are graded according to hardness and solubility, but they vary considerably in dirt and impurities, and from lot to lot in properties and work-

ability. It was this lack of uniformity and difficulty of handling which gave synthetic or chemically prepared resins their chance.

Rosin and ester gum may also be classed with the natural resins. Rosin, a product of pine pitch, is a hard, brittle resin which melts at 80 or 90 C. It has a wide range of application, but for varnishes its use is limited only by its softness and lack of durability and its high acidity. Ester gum is a product of the high-temperature reaction of rosin and glycerine. It is much less acid than rosin and more weather resistant and flexible in a varnish formulation.
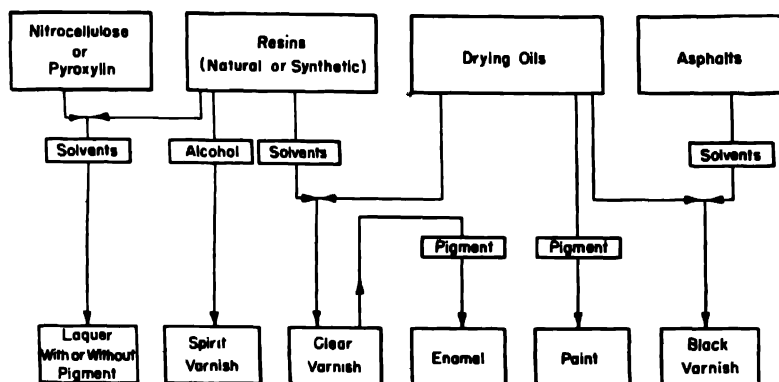
FIG. 10.8. Terminology of paints and varnishes.

Drying Oils. A drying oil is an extract from oil or fat or from a vegetable seed or nut. It is characterized by its ability to take up oxygen from the air and convert to a solid film by the double process of oxidation and polymerization. Polymerization can be defined as a process in which small molecules (monomers) unite with one another to form relatively giant molecules (polymers), either in the form of long chains or cross-tied complex structures. In contrast with the monomers, the resulting solid polymers have higher heat, solvent, and moisture resistance as well as markedly improved mechanical and dielectric properties, all of which are essential to a good insulation material (see Chapter 9). Though some materials will polymerize directly, the drying oils must first undergo oxidation by the absorption of oxygen from air.

Many drying oils have been isolated, but only a few are important for varnish and enamel making. The main ones are linseed, perilla, soya, oiticica, chinawood, and castor oils. Linseed oil is the most familiar and the oldest in history. It is derived from flaxseed by

pressing or solvent extraction. Chinawood oil comes from a nut resembling a huge horse chestnut, the fruit of the Chinese tung tree. Linseed oil is much slower drying than chinawood or oiticica oil and imparts flexibility and life to films, whereas "wood" oil gives toughness and improved water and chemical resistance. Most important of all, particularly for coil-treating varnishes, chinawood and oiticica oil have the almost unique property of setting up rapidly to a gelatinous mass throughout a very thick layer or film. Less oxygen and heat are required for this change than with linseed oil. In addition a process has been developed by which the nondrying castor oil converted into a drying oil. This "dehydrated castor oil" and other synthetic oils are becoming increasingly important in industry.

The terms "short oil" and "long oil," relating to the "length" of a varnish, designate the number of gallons of drying oil to every 100 lb of resin. A short-oil varnish is about 10 gal in length, and a long one may be 70 or 80 gal in length.

The rate of drying of an oil is, of course, connected with the amount of oxygen it can absorb and its chemical structure, but it is not dependent upon these factors alone. The rate also depends upon temperature, light, hygrometric (moisture) conditions, and upon small quantities of accelerating catalysts, called driers. Driers are organic salts of metals, such as cobalt, manganese, and lead, which act as oxygen carriers or catalysts and greatly speed up the polymerization. Very small amounts (a few tenths or hundredths of a per cent) are sufficient for maximum effect. Too much drier often impairs durability and life of the film and may act as a retarder rather than an accelerator.

Asphalts and Pitches. The asphalts and pitches play the same role for black varnishes as the resins do in clear varnishes; they may even be used in combination with resins. Among naturally occurring asphalts (which are mined from veins, much as rock minerals) are gilsonite, a hard, brittle, substantially pure asphalt, and various softer, more plastic materials, such as come from the famous asphaltic lake in Trinidad. There are also available various pitches, which are the end products of the distillation of petroleum, coal tar, wood, and various vegetable oils and fats, chief of which is stearin pitch.

The pitches vary greatly in solubility and melting point or flow point. Some may be modified to give increased elasticity and stability by blowing with air while at high temperature. Their stability in a varnish blend depends greatly upon the cooking and upon the thinner used. The literature abounds in contradictory statements as

to the value of asphaltic materials. They are susceptible to oxidation and are affected by light and heat, failure occurring by the progressive development of fine cracks. When the film is intact, the asphalts are excellent in acid and moisture repellence and have good alkali resistance. They are usually superior to the clear types in dielectric strength and in loss factor but are very soluble in oils. When added to clear varnishes, asphalts retard the drying considerably, unless they are used in sufficient quantity to give additional hardness themselves.

Spirit Varnishes. Spirit varnishes are solutions of shellac, rosin, and other resins in alcohols; usually they contain no oil. They dry chiefly by evaporation of the solvent and are used for quick finishes, sizing, and coating of paper. Some synthetic resins in solution are also used as spirit varnishes.

10.11 SYNTHETIC-RESIN VARNISH

In the last 25 years synthetic-resin development has produced outstanding resins of several types which are replacing natural resins in varnishes and "enamels" where quality, uniformity in composition and performance, and ease of manufacture are factors. The more important and successful types now in established use are the alkyd type, of which Glyptal is an example, and the phenol-formaldehyde type, of which Bakelite is perhaps the best-known example.

Alkyd Varnishes. The chemistry of synthetic resins is elaborate and complicated. The simpler oil varnishes are mere mixtures of dissolved resin and drying oil, but the more useful alkyds have drying oil combined chemically with the resin itself (termed an oil-modified resin). The alkyd resin varnishes may be so formulated that application of heat causes a permanent hardening of the resin to an infusible state, by the process known as *heat polymerization.*

Alkyd resins, especially those modified with drying oils, have become some of the most important synthetic raw materials for finishes and protective surface coatings because of their outstanding gloss, generally superior adhesion, good durability, flexibility, heat and water resistance. In the insulation field they have been slower in gaining importance, but today they are gradually replacing the old black varnishes and compounds. The alkyds are resistant to acids, oil, and chemicals and generally have good impregnating properties. When confined in pockets they are difficult to cure, but they have excellent aging properties under heat. They are also excellent in arc and creepage resistance.

Phenolic Varnishes. Oil-modified phenolic varnishes (in which the oil has reacted with the resin) have met with considerable success in insulation practice. These synthetic varnishes excel in quick baking, through-curing, and bonding strength. They may be also relied upon to serve as an excellent protection against salt-water exposure. The phenolics are, however, much less arc resistant than the alkyd types. The latter are often applied as a surface coat and the combination is superior to either alone.

Formvar Enamels. Chief among the synthetic-resin "enamels" that are replacing the drying-oil type for electromagnet wire insulation are those formulated on the basis of a polyvinyl formal known as Formvar. Wire coated with these enamels is known as Formex. It has outstanding film adhesion, flexibility, and extensibility, as well at toughness and ability to take impact stretching and mechanical abuse. It also has good heat and solvent resistance. These properties have permitted its ever increasing use as insulation applied directly to the conductor where it is needed, thus eliminating or at least greatly simplifying the need for varnish treatment. Formex offers no advantage in electrical strength or space factor over conventional enameled wire. However, Formex possesses such remarkable mechanical properties that it may be used even in the most severe winding applications without the need of a protective covering of cotton, silk, or paper. In this way, savings in space and cost may be made with improved resistance to moisture and heat.

10.12 OTHER SOLID DIELECTRICS

(1) *Extruded, Molded and Laminated Plastics.* There are other molded synthetics, laminated and sheet synthetic materials, and synthetic insulation tubing which are of outstanding importance in the insulation field. These are the cellulose esters (cellulose acetate), the phenolics, the vinyls, the styrenes, and trade products such as Polythene, Teflon, Nylon, and Flamenol. It should be noted that the laminates have considerably less dielectric strength in the direction of lamination than across the layers. This characteristic is especially important where these materials are used for mounting electrical terminals and other electrical parts, since in them longitudinal dielectric strength is needed most. Cloth and asbestos laminates may have as little as one-tenth of the strength longitudinally as across the material; paper-base laminates are but little better, and plastics made with long chopped fibers have values somewhere

between the extremes for laminates. The plastics are discussed in Chapter 11.

(2) *Treated Cloths, Tapes, and Papers.* Treated silk, rayon, and cotton cloths and tapes have advantages which make them particularly useful in electrical insulation. They possess a high degree of flexibility and mechanical strength, and may therefore be wound tightly in place in various motor coils, windings, lead, and cable applications. As a class, they have a high dielectric strength per unit thickness, and some varnished cloths have a fairly low power factor and good aging characteristics. Paper is also varnish treated and used for applications similar to those for treated cloths.

(3) *Compounds.* Under this heading are listed solid, plastic, or semiliquid materials that contain little or no thinner. They may be resins, asphalts, waxes, or varnish bases, or blends of these materials, and may contain fillers, such as talc, silica, quartz sand, mica dust, slate, asbestos, and whiting. Because of this great variety, no classification can be considered exact, but the materials are grouped, for convenience, according to their uses as sealing, filling, or treating compounds.

Sealing and filling compounds are used for protection of windings and for filling cavities in metal, porcelain, and other materials to exclude moisture, dust, and dirt. They may be solid compounds which are melted and poured in place and which solidify on cooling, or they may be plastic or puttylike compounds (such as are used in armature and field coils) which gradually set to a firm condition, with or without heat, according to the particular compound. For filling cavities and for similar operations it is important that the adhesion be good, and that the shrinkage, especially at low temperatures, be as low as possible or like that of the contacting material, so as to prevent cracking. Impact strength, thermal conductivity, and aging at elevated temperatures are also important properties for sealing compounds used on windings. Oil, water, acid, and alkali resistance may be important requirements in certain applications.

Treating compounds are extensively used in producing a solidified mass from which moisture and air are excluded. Coils from which all moisture has been exhausted by a vacuum process are filled with melted asphalt compounds and rendered rigid and moistureproof. A compound for this application should be sufficiently tough to withstand rough handling and should have a uniform flow

point with a good degree of fluidity and penetration at the treating temperature.

(4) *Special Insulations.* A number of materials are now used to regulate the distribution of voltage stresses across the surface or through the body of insulation by means of controlled resistivity (e.g., "Rescon," a trade name derived from resistor and conductor). In general, these materials are used on or in insulation to (a) increase the voltage at which corona will start or "arc-over" will take place, (b) increase dielectric or puncture strengths of insulation, or (c) grade potentials. The proper use of Rescon has sometimes raised the voltage at which corona starts from 3.8 to 50 kv, reduced creepage distances from 18 to 6 in., and increased dielectric strength 20 to 40 per cent at 60 cycles.

10.13   CLASS *B* DIELECTRICS

(1) *Pasted Mica.* Mica comprises a group of natural silicates distinguished by highly developed cleavage. Pasted mica products for use as insulation are made from mica splittings laid in layers on paper or cloth backing and held together with a flexible binding cement or varnish. Shellac and alkyd varnish are the most common binders. Mica tape is used in building up the larger sizes of armature bars and in Class *B* coil insulation. It is taped on coils in the same manner as varnished cloth tape. Flexible or rigid mica sheets are also made with suitable binders. One use is as insulating segments in commutators.

(2) *Varnished Glass Fiber.* Solid glass has long been used for low-voltage insulators and lamps, and it is also used in a flexible fiber form as asbestos and cotton are used. Starting in 1936, the glass companies developed a new method of producing fine fibers in quantity as small as 0.00025 in. in diam. These fine fibers can be spun into thread and woven into cloth and tape. The fiber is both flexible and extremely strong, but when rubbed will abrade rapidly. The bundles of fibers in each thread of glass fiber make it porous, thus limiting the dielectric strength to that of the spacing. These disadvantages make it necessary to varnish treat the glass, which of course immediately limits its high temperature resistance and places it out of the strictly inorganic class into that of the other Class *B* materials. The silicones, or other high-temperature resins overcome these objections to some extent. Treated glass tapes have good electrical properties and water resistance but are not the equal of mica.

The use of glass-fiber insulation is generally limited to the mechanical backing of mica or to low-voltage insulation. It has been used extensively in place of cotton or asbestos on magnet wire. Glass fiber is of interest for uses where space factor is important and stability at high temperatures and in corrosive atmospheres are requisites. In Class *B* applications, advantages of glass as compared with asbestos are those of space, superior heat conductivity, and superior dielectric strength after exposure to moisture when properly treated. A typical application brings the insulation build-up for glass down to 0.006 in. from an original 0.009 or 0.010 in. for asbestos. Sometimes a combination of glass and asbestos fibers are woven together. They have good mechanical strength and increased abrasion resistance, the asbestos acting as a buffer to keep the glass from abrading.

The trend to Class *B* and Class *H* insulations with higher running temperatures and greater output for a given weight of motor may make glass fiber an even more important motor insulation. Solid glass has also been used for high-voltage insulators, e.g., glass transformer bushings with sealed-in metal flanges for subsequent welding, and as glass-to-metal seals for electrical lead-ins on hermetic devices.

(3) *Asbestos.* This mineral, which occurs in long fibers of fairly weak mechanical strength, has a relatively low dielectric strength and is only a fair insulation where the applied voltage is low. Its chief use is on high-temperature windings, such as those in railway, crane, mill, or compressor motors, where severe overloads, together with wide ranges of ambient temperature, may be encountered. Asbestos is also used, sometimes with a protective outer braid, on wire for electric heating devices such as welding machines, ovens, electric irons, and table appliances.

(4) *Polyester Resins.* Permafil is one of the trade designations given to a versatile new group of synthetics whose basic products are thermosetting and which can be modified to produce a variety of materials ranging from soft gels, through rubbery elastomers, to hard tough solids. They are used as: (1) clear liquids of low viscosity for impregnating coil structures, porous bodies, potting and filling, casting, and similar applications, (2) fluids containing large amounts of fillers for casting, sealing and cementing operations, and for coating applications, (3) putties containing large quantities of fillers for cold-molding operations, (4) greases or waxes for fabric or paper coating, particularly for low-pressure lamination, and (5)

varnishes for conventional coil treatment, and coatings for fabric and paper for bonding and laminating. They also have other uses as plastics.

Basically, in their clear, unmodified form, the Permafils are fluids of low viscosities which, when heated, become transformed into solid, infusible materials. Since they contain no solvents, the entire composition is converted to a solid state during the curing cycle. This unique feature insures a complete utilization of the material and freedom from voids, in contrast to conventional varnishes of which one-half or more of the weight is a volatile solvent that must be expelled on baking. Compositions with low volatility have been developed so the Permafils may be applied by vacuum-pressure technique and cured without any complicating loss of material and without the danger of fire hazard.

A typical electrical-insulation-product application is in high-voltage transformer coils where its low power factor over a wide range of temperatures and ability to operate at high electrical stress are important. Other uses are illustrated by rotor coils where good bonding strength is important; potting compounds for lead and junction boxes where low volume shrinkage is important; filling compounds where high heat dissipation and complete filling are needed; and casting around coils of current transformers, filament transformers, reactor parts, and oil-stop cable parts with simple molds.

10.14 CLASS *H* DIELECTRICS

It has been found possible to increase the maximum permissible temperature of Class *B* insulation for Class *H* service by using synthetic *silicone* resins of a predominantly inorganic character.

Silicone is the generic name of a large family of semiinorganic compounds that lie between the organic family of the hydrocarbons and the completely inorganic materials. The body of the molecule of organic hydrocarbon materials is built around chains of carbon atoms, which form carbon-to-carbon networks with other elements. Silicone compounds are similar to these hydrocarbons in their general type of chemical structure except that, in place of the carbon atoms, silicon oxide radicals constitute the chains to which the other elements are attached. The greater thermal stability and chemical inertness of the silicon oxide backbone, as compared to the carbon backbone, imparts to silicone materials their most advantageous properties. Silicones are available as resin solutions, rubber, oils, and greases. With proper solvents the resin solutions become var-

nishes for treating glass cloth or tape, asbestos paper or cloth, and for dipping and impregnating coils. Some serve as stickers for pasting together mica flakes and as binders in assembled insulating systems.

This class of chemical compounds is thermally stable up to 260 C, yet can be applied as varnishes and cured in place. In combination with glass fibers they offer an extension of the temperature limits, thereby permitting more compact design and greater reliability under severe service or overload.

The silicone resins, as a group, are characterized by low electrical losses, by dielectric constants around 4, and by high dielectric strengths. Their resistance to acids and alkalies is generally good, but they are not too resistant to oils and some solvents. Where extreme thermal stability is required, operating temperatures as high as 200 C or even 300 C may be permissible with certain types of these silicone insulations.

10.15 CLASS C DIELECTRICS

Mica, glass, and asbestos are Class *C* materials but, when used with a Class *A* binder, form the intermediate group, Class *B*, or with silicones, Class *II*, and as such have already been discussed. There are other inorganic materials that find specialized application in the insulation field, particularly for high voltage and high temperature.

(1) *Unpasted Mica.* Unpasted mica has a high dielectric strength and very low dielectric power loss. Since it is an inorganic silicate, it has temperature resistance up to 550 C and is unattacked by most acids and alkalies. It is the most generally satisfactory insulation known, but it is more expensive than other insulations because of the labor of obtaining it in split form. White mica (hard potassium, aluminum silicate termed Muscovite from Brazil, India, and the United States) is the type most widely used because it is cheaper and has superior mechanical and electrical properties (see Fig. 10.9). Amber mica (a soft potassium, aluminum magnesium silicate termed Phlogopite from Madagascar and Canada) is used where its resistance to high temperatures or its softness is of importance.

(2) *Porcelain.* American electrical porcelain is a ceramic product made up of clays, quartz, and feldspar. Part of the clay is used to regulate the plasticity of the mixture before firing, the rest to serve as a binder; the quartz is used as an aggregate or filler; the

feldspar acts mainly as a flux. The hardness, refractoriness, and imperviousness of porcelain make it an excellent, weather-resistant, high-voltage insulator which is practically indestructible. These characteristics, however, vary in degree according to the process of manufacture (see Chapter 13).

(3) *Steatite.* Steatite is the name given to a fired ceramic product which contains 80 per cent or more talc bonded with
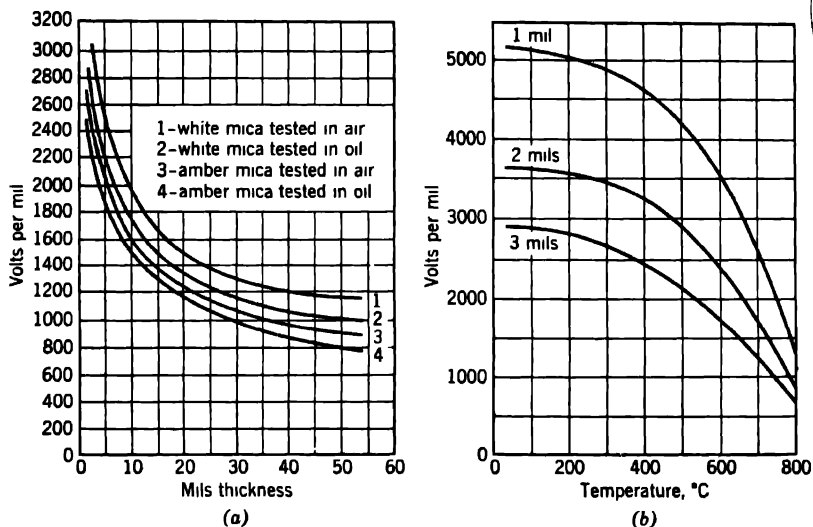
FIG. 10.9. Electrical properties of natural mica. (*a*) Dielectric strength versus thickness. (*b*) Dielectric strength versus temperature for three thicknesses.

ceramic fluxes to a nonporous structure (see Chapter 13). It possesses low loss characteristics needed for high-frequency applications.

(4) *Mycalex.* Mycalex is a trade name for a ceramic product made of glass-bonded mica flakes that possess a combination of properties found in no other insulating material. Though mechanically stronger than porcelain (except in compression), it is not as refractory, but is far superior in this respect to other molded insulations made with synthetic resins, shellac, etc. Mycalex is generally compression or injection molded, though it is successfully machined, and in thin sheets it may even be punched. Aluminum alloys may be cast around Mycalex without affecting it in any way. Its use is particularly advantageous where the requirements demand (*a*) high mechanical strength, (*b*) high dielectric strength

and insulation resistance, (c) low losses at high frequencies, (d) arc resistance, (e) heat resistance well beyond the critical temperatures for molded or sheet organic materials, and (f) a compact construction with metal inserts securely molded in place. A few examples of compression molded and fabricated Mycalex parts are shown in Fig. 10.10.
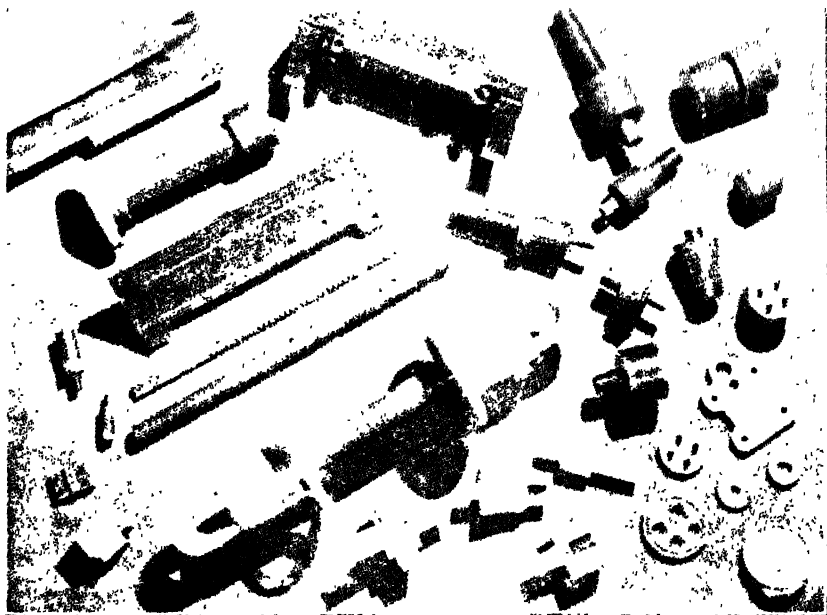
Fig. 10.10. Typical Mycalex parts.

(5) *Oxides.* The mineral oxides that remain stable in air can be used in some applications for high-temperature electrical insulations. Titania (titanium oxide), thoria, beryllia, magnesia, zirconia, and alumina are the oxides that have been found most practical. They may be very finely divided and cast in molds, using only water and a small amount of binder, or a thermosetting-plastic binder may be used which is later burned away. The difficulty of firing the oxides (at 2000 to 3000 C) makes their application very limited. One method of obtaining an oxide insulation that eliminates this difficulty is anodizing aluminum. A heavy, well-bonded coating of aluminum oxide may be formed electrolytically on aluminum and may be used intact as an insulation, but bending and abrasion are likely to cause electrical failure.

Many examples of insulators made of inorganic powders can be found in electronic products. For example, condensers for push-button tuning devices are built with a titanate as the dielectric. These condensers have exceptionally small physical dimensions because of the particularly high dielectric constant (somewhere over 1000) of the dielectric.

A high-temperature application of pressed alumina is found in aircraft engine spark plugs. Not only does alumina offer higher heat conductivity and better high-temperature insulating properties than the porcelain it replaces, but it is also immune to the tetra-ethyl lead of high-octane gasoline, which attacks the silica in porcelain spark plugs.

10.16 DIELECTRIC LIQUIDS

Mineral oils consist of a complex series of hydrocarbons obtained from refining crude oils. Among the most important uses are the cooling and insulating of transformers, regulators, and oil circuit breakers. A low viscosity oil is required in transformers and regulators for effective heat transfer and in circuit breakers for rapid circulation during arc quenching. The dielectric strength, important in all applications, is greatly affected by the presence of certain impurities, principally water, and dissolved gases. It is very important to eliminate moisture from the oil and the part immersed.

Synthetic liquid dielectrics, called askarels (e.g., Pyranol, Inerteen), have replaced the mineral oils in some electrical equipment, because in addition to the desirable characteristics of mineral oil they have the additional property of being noninflammable.

10.17 DIELECTRIC GASES

With the exception of the common use of air at atmospheric pressures (see Table 10.2), the employment of gas as an insulating medium has not reached the stage where it is of practical import to the majority of manufacturers of electrically energized equipment. Nevertheless, it is of interest to note that a few important applications for gas insulation have been developed and that the potentialities are such that gases should not be overlooked.

In place of oil, an inert gas such as nitrogen has been introduced as an insulating medium in power cables (see Sec. 10.20).

A high-voltage X-ray machine extremely compact in size as compared with its predecessors utilizes dichlorodifluoromethane (Freon

Table 10.2 Comparative Values of Dielectric Constant and Dielectric Strength of Typical Insulating Materials

	Dielectric Constant	Dielectric Strength, volts/mil
AIEE Classified Dielectrics		
Untreated dry paper	2	120–125
(nonporous cellulose)	6	
Varnishes		
Spirit	4–5	200–900
Oil	4–5	700–900
Asphalt	4–5	600–1200
Treated paper	3–6	500–1500
Varnished cloth	3–4.5	900–1300
Laminated phenolic		
Paper base	4.5	900–1400
Cloth base	5.5	450–1000
Silicone resin	4	600–2000
Mycalex	8	245–500
Porcelain	6–7	40–280
Mica (white)	65–85	3000–5000

	Dielectric Constant	kv/0.1 in. gap
Liquid Dielectrics		
Mineral oil	2.2	20–40
Pyranol	4–4.5	35

	Dielectric Constant	Dielectric Strength,* volts/mil		
		0 lb/in.² g	50 lb/in.² g	100 lb/in.² g
Gaseous Dielectrics				
Air	1.00059	140	360	580
Nitrogen	1.0005	140	360	580
Freon		270	860	

* Crest voltage across a uniform field (for example, a field between two very closely spaced spherical electrodes). These values should be considered maximum for conditions as specified, because any irregularities, even dust, can cause a tremendous reduction. (For average equipment 75 volts/mil is often used.) The points listed all fall along a smooth curve but no extrapolation is permissible.

12), a gas used in refrigerating systems, as an insulating medium. At the pressure employed, the gas has a dielectric strength several times that of air; thus, 100 lb of gas does the work of approximately 12,000 lb of conventional insulating oil. This achievement has been possible only through careful design to insure uniform fields. The insulating value of compressed gas is critically dependent upon the electric field stresses; dust particles can often cause breakdown.

The application of hydrogen in synchronous generators and in condensers may well be mentioned here. Though hydrogen is used principally to improve heat conduction and reduce windage losses, it also inhibits the deleterious effects (caused by the destructive action of the activated oxygen on insulation material) accompanying corona discharge in air.

Some Typical Applications of Insulating Materials

10.18 WINDINGS

The two main types of windings for motors and generators are random and formed windings. Random winding refers to a winding process whereby the wire, usually round, is wound into slots; the wires lie in whatever position they happen to be laid down.
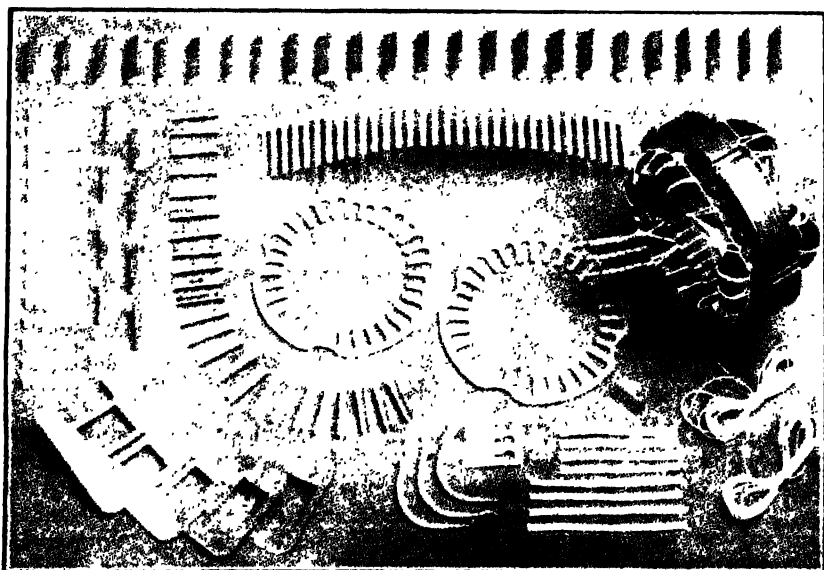
FIG. 10.11. Insulation material used in a random-wound induction-motor stator.

the wires lie in whatever position they happen to be laid down. Formed windings are either coils formed to exact shape or are built up of rectangular conductors and bent to shape before being inserted into the slots. Size, voltage, rating, efficiency, power factor, service requirements, and cost determine the choice of winding type.

Random windings are used in so-called closed slot motors, which include all the smaller sizes of fractional horsepower and induction

motors (see Fig. 10.11). The wire used is generally Formex or enamel treated. The latter may also be protected from mechanical injury by a bonded covering of paper or cotton. It is important that the windings be further protected from the sharp edges of the punchings by slot insulation made up of treated or untreated papers or varnished cloth. If insulation between phases is needed, it usually consists of varnished cloth and treated paper inserted between the proper coils. To provide a tight fit for good thermal conduc-
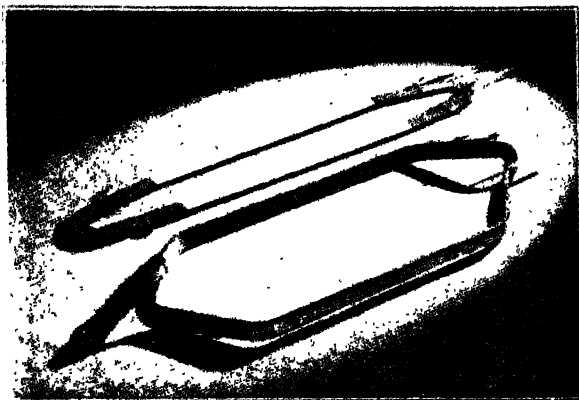
FIG. 10.12. Induction motor coils of rectangular wire before (top) and after (bottom) being "pulled out" and formed.

tivity, a processed wedge (wood, laminated plastic, or fiber) may be driven in over the windings, and a varnish treatment may then be applied to provide a solid bonding to the whole assembly. The end turns of some of the larger sizes may be imbedded in phenolic molding compound, whereas smaller sizes generally are retained by ribbon or cord ties.

Form windings used in small open-slot motors are made of rectangular wire. The coil is first wound by machine into a lopsided loop or hairpin form (Fig. 10.12), varnish treated, the slot portion heat molded to size, and the coil then pulled out into the familiar hexagonal form. Form windings for large machines cannot be conveniently pulled, hence they are wound to finished form. The coils may be taped after forming, with cotton, varnished cambric, glass fiber, asbestos, or pasted mica tape, and given one or more varnish treatments. When inserting the accurately formed coils into the proper slots, care must be taken to avoid mechanical injury by impact or abrasion and yet get as tight a fit as possible.

The smaller-size induction motors up to 660 volts use Class *A* insulation, but larger machines may make use of a composite insulation, which permits less insulation build-up in some instances. The composite employs pasted mica tape on the inside and varnished cloth on the outside for slot or ground insulation.

Mica systems are utilized in rotors for the larger machines and stators above 5000 volts or 5000 kva (see Fig. 10.13). Class *B*

FIG. 10.13. Large mica-insulated coil being taped.

coils made with asbestos or glass turn insulation are used for railway motors and other motors subjected to overloads and high ambient temperatures. Class *H* insulations extend this range by 50 degrees.

Control or magnet coils of many varieties and uses are wound with bare enameled wire in layers, each separated by paper, the enamel being more than sufficient insulation for one turn. A varnish treatment further insulates the turns and layers and provides good bonding. Other control coils are random wound, and certain high-current coils are wound edgewise with strap copper. These edgewise-wound coils usually have several varnish coats directly on the bare copper. Asbestos, ground mica, or paper spacers are sometimes used, and the coils pressed down to size. Interpole coils, commutating coils, and some solenoid-type coils are made in this manner.

10.19 VARNISH APPLICATIONS

The principal use for insulating varnishes is in the treatment of porous insulation such as cotton, paper, and asbestos, where such insulation is used in coils on electric apparatus such as motors, control coils, transformers, etc. The varnish may be applied before the coil is wound or, in many instances, it is used for treating a completely wound coil or assembly, wherein it serves the function of not only filling the porous insulation but the interstices between coil turns and coil assemblies. The varnishes also serve as a bonding agent in coils and assemblies and may be used without further protection, or they may be coated with a protective insulating surfacing material.

Other uses for varnishes are: (1) pasting or cementing together portions of insulating material, such as built-up pasted mica, or applying tapes to formed coils, (2) pretreatments for cloth and paper to be wrapped or wound tightly on cables, motor coils, winding, leads, etc., and (3) building up film insulation directly on wire for coils and on sheet iron or steel laminas for armature, field, or solenoid cores. The smaller cores may provide intersheet insulation against eddy currents with oxide coatings produced by blue annealing. The larger machines, however, use baked core-plate enamels, sometimes with mineral fillers, e g., zonolite, which is a finely ground mica.

The consistency of a varnish is controlled for application by the addition of thinner. The best control is to maintain viscosity, but for single materials specific gravity can be used. The varnish should be kept at room temperature, since a cold varnish flows poorly and does not penetrate well, and high temperatures cause chemical changes and thickening. Covered storage should be employed to prevent dirt contamination, loss of solvent, and oxidation (skinning). Thinner, when needed, should be added slowly and at the same temperature as the varnish. The solvents, when mixed with air, are inflammable, explosive, and somewhat toxic. Adequate ventilation should therefore be provided to keep concentrations below the explosive or toxic limit. Safeguards should also be provided to eliminate contact of wet varnish and solvents with the skin, since some workmen are sensitized by repeated contact.

To obtain the best results, all surfaces to be coated should be clean, dry, and free from grease and dirt. Metal parts should be carefully pickled, or, if the presence of insulation prevents such

treatment, thoroughly washed with a suitable solvent. Where a smooth finish is desired, nap may be removed from tapes or threads by singeing. Any small particles on the work at the start may increase in size and become more unsightly after each varnish coat.

The chief methods of varnish treatment are listed below. All are used in the impregnation of coils and will therefore be discussed in that connection.

      (*a*) Dipping:
             1. Without prebake.
             2. With prebake.
      (*b*) Vacuum filling.
      (*c*) Pressure filling.
      (*d*) Combinations of (*b*) and (*c*).
      (*e*) Brushing or coating (as coil is wound).
      (*f*) Use of pretreated materials.

Dipping is the oldest and simplest method of treatment. In filling a deep coil, it is least effective of all processes, but the penetration is materially aided by prebaking the structure which may also remove moisture. A process termed *flashing the enamel* is used on core plates for purposes somewhat similar to those achieved in coil prebake. The core plate enamel is set afire to burn out the solvent and preheat the punching before baking.

Better penetration and filling are obtained by evacuating all air from a coil, in addition to removing the moisture, and then dipping before the vacuum is released. Still better results are obtained by following the vacuum cycle with a pressure cycle; i.e., while the coil is still submerged after the vacuum cycle, the liquid varnish is put under pressure. Sometimes the pressure cycle alone may be used; however, with either, the fluid pressure molds the insulation solidly to the conductors and causes additional filling of ground coats. These methods, of course, require larger initial outlay in equipment but they eventually result in better and less expensive processes and products.

With materials such as drying-oil varnishes that depend on oxidation to harden, bulk filling results in tacky coils because oxygen is sealed out by the hard-surface film. If use is made of the polymerization of chinawood oil, baking at high temperatures (125–150 C) for several hours is required for hardening. A combination of phenolic-resin-hardening and chinawood-oil-polymerization in a varnish provides the best balance between practical speeds and tem-

peratures of hardening-in-mass to give required physical, chemical, and electrical properties for general service.

The hardening characteristics differ for spirit varnishes, air-drying varnishes, and baking varnishes. Spirit-varnish films are practically useless as electrical insulation because the brittle resin or gum base is usually incapable of undergoing oxidation or polymerization, with accompanying improvement in mechanical and dielectric properties. The initial film obtained from them is soft and pliable, because of the solvent present, but when this evaporates the film becomes brittle and cracks, and may even granulate. Air-drying varnishes are also poor because the very thing that causes their rapid hardening is ultimately the cause of failure; the driers do not stop their oxidation process at the best place but continue until the film becomes brittle or weak. Baking, when performed properly, removes the last traces of solvents and moisture, and hence produces the most uniform and stable surface. With synthetic varnishes, baking promotes the conversion of resin or varnish base to an insoluble state and can produce in a few hours properties that are desirable from an insulation standpoint and which weeks of air drying could not produce.

The hardening process is complex, and any insulating method should take into account the chemistry of the materials and insure that adequate opportunity is provided for the following: (a) Complete penetration and filling, (b) complete removal of solvent, (c) polymerization of the varnish to a hard or gelatinous state where optimum properties are obtained, (d) removal of volatile oxidation and polymerization reaction products as far as possible before surface setting takes place, (e) retention of maximum varnish base in windings, and (f) minimum injury to insulation on wire already in the assembly, either from heat, solvents, or mechanical forces. Best results are obtained, in general practice, only by allowing sufficient time to accomplish these effects.

The ideal filling or impregnating varnish would be one that would penetrate readily into the deepest, tightest coil and remain there while by some simple process it is converted into a permanently hardened material in the shortest possible time without injury to the turn insulation. Such an ideal material should not have a solvent that would evaporate during curing. Materials such as the Permafils may achieve this goal, in that they contain no volatile matter that must be expelled during application (the conventional varnishes contain about 50 per cent volatile solvent by weight)

and, in addition, are converted to a solid mass uniformly through-out any thickness simply by heating at moderate temperatures with-out the aid of oxygen from the air and without the formation of volatile reaction products. The resulting products have exceptional heat, water, acid, and alkali resistance and good dielectric and mechanical properties. They are finding more and more use in coil treatments as well as sleeving, coatings, tubing, etc.

10.20   CABLE INSULATION

Electric supply cables are insulated with rubber, extruded thermo-plastic, varnished cambric, or paper, and the paper insulation may be of the solid, gas-filled, or oil-filled type.

The choice between rubber, extruded thermoplastic, varnished cambric, and solid impregnated paper insulation is generally based upon voltage, cost, and ease of handling during installation. Rubber and thermoplastics are widely used at the lower voltages (below 5000 volts), and where their resistance to moisture and flexibility are of special importance, or where labor skilled in wiping lead sleeves is unavailable. High-voltage rubber cables are made for ratings up to 15,000 volts, but varnished cambric and impregnated paper may be preferred where voltage, temperature conditions, and cost are unfavorable to rubber. Lead-covered (to keep out mois-ture) impregnated paper insulation is cheaper than lead-covered var-nished cambric, and in many of the larger systems it is used ex-tensively for all voltages. As voltage goes up, dielectric losses be-come more important, and since varnished cambric is somewhat poorer in this respect than impregnated paper, it rarely is used above 15,000 volts.

Figure 10.14 illustrates four types of cable construction. In each, the insulating material has been applied to the individual conduc-tors and a series of coatings added to protect against moisture or mechanical injury or both. Because the conductors are round in the three conductor cables shown, a filler has been used to fill out the circular cross section of the cable. The "belt" serves both to bind the conductors and filler together and as part of the insula-tion to ground.

Approximately 85 per cent of service failures of solid-type paper-insulated cable are from causes not inherent in the insulation, i.e., mechanical injury to the cable, corrosion of lead sheath, splits due to high and uncontrolled internal load cycle pressures, or leaks in wiped joints and fittings. Solid-type paper and varnished cambric

insulations give no warning of these troubles. With gas-filled impregnated paper cable (Fig. 10.15), loss of pressure serves as a prompt indication. Pure, dry nitrogen gas at 10 to 15 lb per sq in. is distributed throughout the cable length. (With medium-pres-
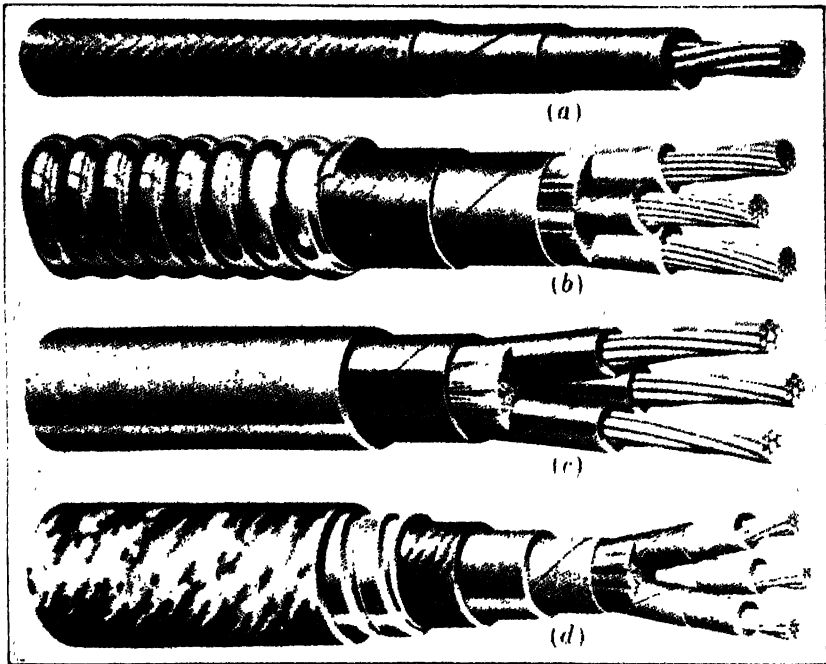
Fig. 10.14. Typical cable constructions. (a) Rubber-insulated cable with weatherproof braided finish (single conductor stranded). (b) Varnished-cambric insulated cable with filler, belt, braided finish, and interlocked spiral steel armor (three-conductor stranded). (c) Varnished cambric insulated with filler, belt, and lead sheath. (d) Parkway cable with rubber-insulated conductors belted, lead covered, projected by jute, interlocked armor, and jute over-all.

sure gas-filled cable these values are 35 to 45 lb per sq in.) Because of the maintenance of uniform gas pressure, less insulation is required than for solid-type cable. It has been possible to increase the dielectric strength still further by using gas pressures of 200 lb per sq in. in special casings, but suitable applications for this construction are very rare.

Oil-filled paper-insulated cables are used at 27 kv and above, and are used exclusively above 69 kv. The oil pressures range generally from 1 to 15 lb per sq in., the oil being distributed throughout the

cable from reservoirs permanently connected to the cable. This type of cable was developed to overcome the voids caused by migration of the insulating compounds used in solid cable (such as
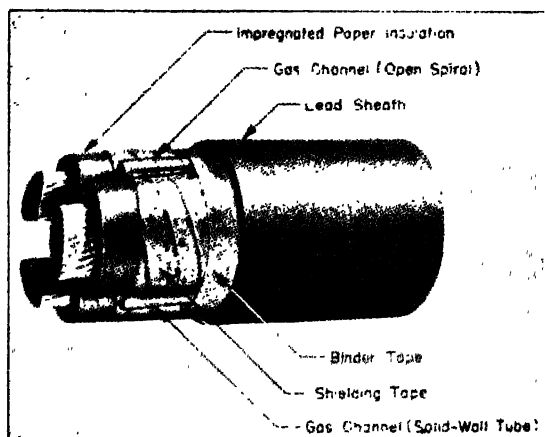
FIG. 10.15. Gas-filled cable construction.

plastic flow of compound away from sections of cable lying at the top of steep slopes). Instead of supplying the insulating oil through small tubes within the cable cross section, one type of system has a steel casing around the paper-insulated conductors which is filled with insulating oil under pressure as high as 200 lb per sq in. Here again the system is better suited to very special applications than to general use.

10.21 CONCLUSION

Even though the best of the available materials is applied in accordance with the best practice, service experience may still show insulation weaknesses if some factor of importance has not been considered in the design. New insulations, new applications, and new treatments, therefore, are best accepted only after satisfactory performance in accelerated tests simulating service conditions.

In considering design problems in the manufacture of electrical apparatus, a knowledge of existing insulating materials and their properties, as related to coil design, manufacturing, assembly and service requirements, is most desirable if progress is to continue. A consciousness of the importance of insulation to motor, coil, and cable life, and a constant effort to reduce costs of materials and

methods by using the best engineering methods of approach, will result in improved quality and reduced apparatus costs.

Review Questions

1. What is the primary purpose of insulation?

2. (a) Name at least six criteria which might be used in various applications as the basis for selecting an insulating material. (b) Tell how each of the characteristics named might be measured in the laboratory.

3. (a) What are the limiting temperatures for each of the five AIEE insulation classes? (b) In what insulation class or classes is varnish? mica? cotton?

4. If the ambient temperature for a motor-coil insulation application is 40 C, what is the maximum surface-temperature rise permitted by AIEE classifications for a Class A material? for a Class H material?

5. (a) What are the sources of drying oils? (b) Distinguish between a "short oil" and a "long oil."

6. (a) What is a "spirit varnish," and what are spirit varnishes used for? (b) What are the outstanding qualities of alkyd resin varnishes? of Formvar?

7. (a) Discuss the relative advantages and disadvantages of white mica and amber mica, and tell where they are most often used. (b) List the advantages and disadvantages of glass fiber insulation for motors.

8. (a) What are the compositions of steatite and Mycalex? (b) For what type parts are they used?

9. (a) What harm may result if the air spaces in a coil are not filled with the insulating medium? (b) If varnish dipping does not give sufficient penetration, what measures might be taken to cause the coil to fill completely?

10. Name three types of cable insulation, and the kind of application in which each is most generally used.

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11 PLASTICS

by A. M. VARNER *

11.1 INTRODUCTION

In the broadest sense, a plastic is defined as any nonmetallic material that can be molded to shape. This definition has been narrowed, however (more or less by common consent), to include only a certain group of natural and synthetic resins and their compounds that can be molded, cast, extruded, or used for coatings and films. Practically all these resins are of an organic nature, composed of combinations of hydrogen, carbon, oxygen, and nitrogen. The chief source of raw material is from coal, petroleum, and agricultural products.

Bituminous plastics were used industrially in the eighteenth century, and pyroxylin, shellac, and casein plastics were developed in the nineteenth century. The real beginning of the modern plastics industry was marked by the announcement of Dr. Baekeland in 1909 of the development of phenol formaldehyde plastic. Since then, research has developed many new plastics which have become commercially important.

Plastics are basic engineering and fabricating materials having unique and an almost infinite variety of properties. The properties common to most all plastics are light weight, resistance to deterioration by moisture, low electrical conductivity, low thermal conductivity, and a good color range. The choice of resins and suitable modifiers offers to the engineer plastics that are very flexible or rigid, low melting or heat resistant, spongelike or water repellent, brittle or extremely tough, easily soluble or highly resistant chemically, and electrically conductive or electrically insulating. Standard forms in which plastics are available include molding powders, sheets, films, rods, tubes, and liquids. Contrary to popular belief, plastics are not inexpensive and usually are competitive pricewise with other engi-

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neering materials only because of (1) their adaptability to high-volume low-cost production, (2) the savings effected by little or no need for machining or finishing operations, and (3) the possession of a combination of inherent properties not found in any other materials. Propertywise, a plastic can be found for virtually all applications except those involving high (above 500 F) temperatures and very high strength.

11.2 CLASSIFICATION

The most common classification of plastics is under thermoplastic and thermosetting materials. The thermoplastics are those which when heated begin to soften at temperatures as low as 140 F, then can be molded without any change in chemical structure. The thermosetting materials undergo a chemical change when molded and cannot be resoftened by heating to reshape them. The mold temperatures for the thermosettings are usually considerably higher than for the thermoplastics, and the finished product is capable of withstanding much higher temperatures without deformation. Listed below are most of the common plastics designated according to these general categories:

Thermoplastic	*Thermosetting*
Acrylics	Alkyds
Cellulosics	Epoxides
Fluorocarbons	Furan
Natural	Inorganics
Shellac	Melamines
Asphalt	Phenolics
Etc.	Polyesters
Nylon	Silicones
Polyethylenes	Ureas
Polystyrenes	
Polyvinyls	
Protein substances	

11.3 COMPONENTS OF MOLDING COMPOUNDS

Various materials such as fillers, plasticizers, lubricants, colorants, and stabilizers are incorporated into many plastics to impart special properties not inherent in the basic resins.

The resin is the principal component of the compound, gives the compound its name and classification, and imparts the primary prop-

erties to it. It is the cohesive and adhesive agent which provides rigidity, and binds together the filler particles. The resin may be used by itself without the addition of a filler, as in cast phenolics; usually, however, it is combined with one or more of the other components.

The filler is usually an inert fibrous material used to reduce cost, improve impact strength, temperature resistance, chemical resistance, electrical resistance, etc., which is normally employed with thermo-setting materials. For common fillers and their uses, see Table 11.1.

Table 11.1 Common Fillers and Their Uses

Filler	*Purpose*	*Remarks*
Wood flour	Low-cost bulk; improved flexural and impact strength	White pine usually used up to 60%—high percentage decreases luster
Mica	Electrical and heat resistance	Ground mica used
Alpha cellulose	Improved flexural and impact strength	Especially valuable in translucent ureas
Cotton flock	Improved strength	Poor finishing properties
Paper	Impact strength	Pulp usually used
Macerated cloth	Impact strength	Not as high impact strength as woven cloth but also less expensive
Rosin	Dilutent	Low cost
Asphalt	Binder	Low strength
Talc	Acid resistance	.
Asbestos	Insulating properties; heat and fire resistance	Poor finishing properties
Graphite	Internal lubricant	
Carbon	Chemical resistance, conductivity	
Gypsum	Flame proofing	
Canvas	Resilience, strength	Used in silent gears
Rock flour	Cheap bulk and weight	

Plasticizers are high-boiling liquids (200 F to 400 F) used to improve flow of resins and to make finished parts more flexible.

Lubricants are used to prevent molded pieces from sticking in the mold. Lubricants may be incorporated into the molding compound or applied directly to the surfaces of the mold. Materials such as lanolin, linseed oil, mineral oil, castor oil, paraffin, graphite, and metallic soaps are common lubricants.

Colorants, dyes, toners, and pigments all find a place in plastic pieces. The selection of the proper coloring medium must take into consideration the effect of the colorant on flow, hardness, adhesion,

curing rate, dielectric properties, etc., of the plastic, as well as the properties of the colorants themselves, such as translucency, hygroscopicity, uniformity, odor, compatibility, chemical resistance, and nonbleeding or fading.

Catalysts (or hardeners) are necessary in controlling the rate or extent of polymerization of the resins.

Stabilizers (or inhibitors) are included to increase the pot life (time between mixing and use of the mixture) of a material or to prevent color change or other deterioration on aging.

Thermoplastics

11.4 ACRYLICS

The principal acrylic resin is *polymethyl methacrylate,* commercially known as Plexiglas and Lucite.* The family of acrylic and methacrylic resins are derivatives of acrylic acid and range from viscous liquids to hard thermoplastic solids. The softer resins are used as elastic adhesives and, in an aqueous dispersion, as a finish for cloth and leather. The monomers are used as casting resins for casting the sheet material like that used for transparent aircraft turrets and cockpit enclosures. The polymer, polymethyl methacrylate, is available as a molding compound.

The outstanding properties of the cast sheet and the molded forms of the polymethyl methacrylate are their exceptional transparency and clarity, lightness, rigidity, and good weather resistance. The various forms in which it is available make possible a wide variety of uses, such as dentures, transparent enclosures, goggles and lenses, castings, and extruded tubing.

11.5 CELLULOSICS

Cellulose nitrate, the original Celluloid of white-collar fame, is made † by the reaction of nitric acid and cotton linters. This plastic was first developed in 1869 to provide a substitute for ivory in billiard balls, thus making it the first true synthetic plastic. It is still widely

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* Trade names are mentioned in this chapter since plastics are better known by these names than by their chemical names. The intent has been to include trade designations from usual sources for each product. Any omissions are unintentional.

† The compounds of the cellulose group are all derived from the digestion of cotton linters by an acid. The precipitated esters are then mixed with plasticizers, dyes, and solvents to produce molding and extrusion compounds.

used for the fabrication of fountain pens, toothbrush handles, spectacle frames, eyeshades, etc. Cellulose nitrate is available as lacquers and emulsions, as extruded rods and tubes, and sheets 20 by 50 in. from 0.005 to 1 in. thick. The finished material is quite flammable and is difficult to mold; however, its advantages of toughness, water resistance, and a wide range of attractive colors and mottles makes it a favorite for many applications. Trade names are Hercules CN, Nitron Nixon CN, and Pyralin.

Cellulose acetate * overcomes the chief disadvantages of cellulose nitrate; it is less inflammable and molds very readily. It was first marketed as a molding compound in 1929 and did much to advance the practice of injection molding. Finished cellulose acetate products are tough, smooth finished, resilient, tasteless, and odorless. The material is available as transparent, translucent, or opaque, and in all colors and a variety of mottles and variations. Cellulose acetate is especially adaptable to extrusion, and is available as rods, tubes, trim, and other standard shapes. It is not suitable for parts in contact with water and loses its mechanical strength at subzero temperatures. As a molding compound its mechanical properties and its moldability and extrudability make it a favorite compound for small items which must take a lot of abuse, such as flashlight cases, tool handles, goggles, combs, pencils, and kit boxes. Transparent sheets are being used as aircraft enclosures, specially formulated to decrease the sunburn suffered by pilots, and as a covering for wire screen to make a transparent shatterproof window. Trade names are Fibestos, Hercules CA, Lumarith, Nixon CA, Plastacele, Tenite I.

Cellulose acetate butyrate excels cellulose acetate in regard to dimensional stability and moisture resistance. Otherwise, it is very similar as to manufacture, properties, and availability. Because of its special properties, this material fills applications such as radio dials, weatherstripping, hose nozzles, ammunition rollers, telephones, football helmets, vacuum-sweeper parts, irrigation tubes, and pipelines for petroleum products. Trade name is Tenite II.

Ethyl cellulose † has recently found a ready welcome in the plastics picture because of its special properties of toughness at low temperatures, excellent dimensional stability, and improved chemical re-

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* The material is made by treating cotton linters with acetic acid; the cellulose acetate formed is compounded with a plasticizer and is then pressed into large blocks or ground into molding powder.

† This plastic is made by treating cotton linters with sodium hydroxide and then ethylating the alkali cellulose.

sistance. The principal applications are as lacquers and fabric dopes, strippable coatings to protect the sharp edges of machine tools against chipping or corrosion during shipment or storage; injection-molded parts such as screwdriver handles, fountain pens, toilet seats, and clock cases; and extruded tubing for irrigation. Trade names are Ethocel and Hercocel.

Regenerated cellulose is more commonly known as Cellophane. It is prepared by extruding a viscose solution from a long narrow orifice through a coagulating and washing bath. The film is then rolled onto mandrels and made into Cellophane sheet which is used principally for decorations and packaging.

Vulcanized fiber is made by treating a cellulose paper with zinc chloride, so as to laminate the layers and toughen the fibers. It is somewhat similar to a laminated product. It can be formed only to simple shapes but can be readily machined, sawed, drilled, tapped, or punched. Fiber sheets are exceptionally strong and tough, especially on a strength-weight basis, have good dielectric and arc resistance properties, and good chemical resistance (see Chapter 14).

Methyl cellulose, formed by the methylation of cellulose with dimethyl sulfate, is a water soluble, tasteless, odorless, nontoxic material available in film form It is highly flexible and resistant to grease. The chief uses of this material are as a coating for paper and in powder form as a thickening agent—trade name Methocel.

Benzyl cellulose is one of the most water resistant of the cellulosic materials, with low flammability and good electrical properties. As a molding material, its applications are very limited because of low strength properties.

11.6 FLUOROCARBONS

Fluorocarbons such as Teflon * and Kel-F † are materials that exhibit outstanding chemical inertness and heat resistance as well as excellent electrical-insulation properties. Both these fluorocarbons are available as thin films, sheets, rods, tubing, molding powders, and suspensoids. Polytetrafluoroethylene (Teflon) requires special molding techniques because the polymer does not melt and flow. The part to be molded is preformed by compressing the granules to the desired shape, and then heating to 620 F, where the polymer undergoes a

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* Produced by the complete fluorination of chloroform plus subsequent polymerization to polytetrafluoroethylene.

† Produced from the partial fluorination of freon plus subsequent polymerization to polymonochlorotrifluoroethylene.

transition to an amorphous gel which allows the particles to fuse together to form a part of good strength. Extruded products are produced in essentially the same manner. Because of the chemical inertness and waxlike surface of the polymer, it is difficult to bond the material to itself by adhesives, but bonding can be accomplished by electronic sealing techniques. By the incorporation of metallic powders into the polymer prior to molding (in a special technique developed by the United States Gasket Co.) it is possible to form insulators that can be electroplated. This method is used to form hermetically sealed joints for transformer lead wires. The nonadhesive property of Teflon has led to its use in applications involving the handling of sticky materials, such as bread dough, and for heat sealing plates on packaging equipment.

The monochlorotrifluoroethylene (Kel-F) possesses nearly the same desirable properties as the tetrafluoroethylene, with the additional advantage of ease of fabrication. It lends itself readily to extrusion, injection, or compression molding.

Except for molten alkalies, and under some conditions fluorine, which attacks the fluorocarbons, there is no known solvent for these materials. They may be used as low as -100 F and as high as 500 F. Materials of this type can be given additional strength from orientation by cold drawing or rolling. When thus treated the plastics will revert to their original shapes when loads are released. Because of the extremely high cost of fluorocarbons their use is somewhat restricted to applications involving hot and corrosive liquids and as insulations in high-voltage and high-frequency electrical equipment.

11.7 NATURAL RESINS

Natural resins include shellac, bitumen, rosin, asphalt, pitch, and copal. They are of a thermoplastic nature and were the first type of plastic to be used. Shellac is still an important natural resin as a coating compound. For a considerable period of time it was the main material used in the manufacture of phonograph records. It has excellent electrical properties and is used in molded and laminated parts (see Chapter 10).

11.8 NYLON

This is the most widely used of a group of plastics of nitrogenous structure known as the *polyamides*. The polyamides are crystalline in nature and can be so processed as to orient the crystals axially thus making the tensile strength of fibers extremely high. This out-

standing property makes nylon especially valuable in the extrusion of filaments, which are subsequently wound into thread and woven into hosiery, fabrics, or rope. They are also used directly as bristles, sutures, etc.

Molded nylon parts are extremely tough and resistant to abrasion and heat. The heat resistance exceeds that for most thermoplastics and strength is well retained nearly to the melting point of about 400 F. One of the first applications for molded nylon was for bearings and for gears for high-speed light loads and low-speed heavy loads where the nylon required no lubrication. Water and grease lubricants may be used with nylon. Nylon may be molded in very thin sections and will flow around complicated inserts. The combination of toughness, resistance to water, heat, light, and chemicals plus elasticity and excellent electrical properties makes nylon a superior wire-insulation material. The electrical properties of some grades are considerably affected by temperature in the range of 150–170 F, a property which has been employed for detection purposes (e.g., safety device on an electric blanket).

11.9 POLYETHYLENES

This material originated in England and was first produced commercially in the United States in 1943. Polyethylenes are the product of straight-chain polymerization of ethylene and are obtainable as viscous liquids, gums, and tough flexible solids suitable for molding. The solids are waxlike in appearance, translucent, odorless, and one of the lightest of plastics (sp gr 0.92). They are flexible over a wide temperature range, resist moisture, possess good electrical properties, are chemically resistant, and are relatively low in cost.

Blow molding may be used to produce all forms of flexible containers and this material is replacing bottles in many instances. Large shapes may be formed by heat welding. Coatings are applied by flame spray, hot melt techniques, or deposition from dispersions. Applications include pipes and fittings for chemical plants, flexible bottles for many kinds of liquids, including hydrofluoric acid, liners for shipping containers, refrigerator parts, electrical wire and cable insulation, and electrical tape. The properties, ease of fabrication, and low cost are making this one of the most widely used of all the plastics.

Polyethylene has a high coefficient of contraction, and careful attention should be given to the design of parts to facilitate molding. Trade names for this material are Polythene, Alathon, and Plaxpak.

11.10 POLYSTYRENE

Polystyrene resin,* in granular form, is used directly for injection molding or extrusion, usually without the addition of any plasticizers, fillers, or lubricants. The resin is a clear, hard, light thermoplastic without odor or taste. Parts made from polystyrene have a distinctive glasslike tinkle when dropped. The outstanding properties are its low specific gravity (1.05), its excellent resistance to inorganic chemicals, its low water absorption, its excellent dimensional stability, and its excellent electrical properties and low cost. These important properties have made polystyrene especially applicable to such items as battery boxes, chemical equipment and closures, radio and television insulations, refrigerator parts, lenses, and jewelry. Polystyrene tends to discolor under sunlight and it therefore is not suitable for use in outdoor applications where appearance is important.

Polystyrene is a somewhat brittle material, but a product of higher impact resistance and flexibility is obtained by copolymerization with acrylonitrile. The higher impact material, having a milky white color, loses the advantage of the crystal clarity of the regular polystyrene. Trade names are Styron, Lustrex, and Koppers P S.

11.11 POLYVINYLS

The polyvinyls include plastics which may be subdivided as polyvinyl alcohols, esters, acetals, and halides. In these classes are the following resins which are commercially important and of interest to the designer: vinyl acetate, vinyl chloride, copolymer of vinyl acetate and vinyl chloride, vinyl butyral, and vinylidene chloride.†

Various formulations of the vinyl resins present an exceptionally wide range of properties and applications. They exist as viscous liquids or may be formulated into flexible or rigid solids. The property of flexibility at ordinary and subzero temperatures has led to the substitution of vinyl resins for rubber.

Polyvinyl acetate is available in various viscosities of the solid resin and in organic solvents and water emulsions. Mixed with filler it can be used for moldings and plastic woods. Its chief use, however,

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* Styrene resins are made from ethyl chloride and benzene, which are derived from petroleum and coal respectively.

† Acetylene passed through acetic acid produces vinyl acetate or reacted with hydrogen chloride yields vinyl chloride. If the vinyl acetate and vinyl chloride are polymerized together, a copolymer results. Polyvinyl butyral is made by reacting polyvinyl alcohol with butyraldehyde. Vinylidene chloride is a product of the reaction of ethylene (from petroleum) and chloride (from brine).

is as an adhesive and as a sizing or coating. As such it is used for food cartons and drinking cups, and for laminating cellophane. Trade names are Elvacet and Vinylite.

Polyvinyl chloride without plasticizers is a hard, horny, nearly unworkable material. It may be plasticized through a wide range of flexibility. By the dispersion of finely divided polyvinyl chloride resin in a liquid plasticizer, viscous liquids called *plastisols* are formed. By application of heat, the liquid plastisol is gelled into a solid by the solubilization of the resin in the plasticizer—the products ranging from soft rubberlike to firm tough materials. Parts are thus easily formed by casting, dipping, or slush-molding techniques. The cured plastisols exhibit properties of good resistance to oils, petroleum-based solvents, and most acids and alkalies, good electrical properties which are retained more permanently than rubber products, good abrasion resistance, and good colorability. By the addition of metallic soaps or an excess amount of filler, a puttylike consistency can be obtained in the uncured plastisol which will not flow under the heat of curing, thus allowing parts to be formed and then cured outside the mold.

Applications for the plasticized polyvinyl chlorides in the film form include such things as shower curtains, foul-weather wearing apparel, upholstery materials, household drapes, and bags. Plastisols are used as potting compounds for electrical coils, coatings for dishracks, protective coatings for metals, lifelike dolls, and rubberlike toys. Extruded and molded products have been refrigerator gaskets, floor tile, tubing, light plugs, and heavy-duty shoe soles and heels.

Unplasticized rigid polyvinyl chloride can be fabricated in useful shapes by hot-gas techniques and is used for ducts and tank liners for corrosive mediums.

Common trade names are Geon or Koroseal, Vinylite, Tygon, Marvinol, Flamenol, and Lucoflex.

The acetate-chloride vinyl copolymer combines the best properties of the individual resins into one. Compounds of low molecular weight and a high percentage of vinyl chloride are used for molding powders and sheet stock. Solutions of the resin in acetone are used in the manufacture of Vinyon, an extruded filament used in the making of dental floss, woven fabrics, filter cloth, etc. Other solutions and coatings are used for lining food cans, waterproofing raincoats, and coating paper. By highly plasticizing the vinyl copolymer resin, flexible and rubberlike extruded and molded parts, sheet stock and film may be made. This material is being used in clothing accessories

such as wallets, belts, and suspenders, and in applications such as gaskets, covered wire and shower curtains. Unplasticized sheet stock and molded parts are noted for their dimensional stability and are used to fabricate charts, dials, and drafting and calculating instruments. Trade names are Tygon and Vinylite.

Polyvinyl butyral is a similar type of flexible sheeting, which has found its main use as the interlayer of a safety-glass sandwich. In that capacity it provides properties of elasticity, toughness, and good adhesiveness. Trade names are Butacite, Butvar, Saflex, Vinylite.

Vinylidene chloride is also known as Saran, and has a number of unusual properties. Chief of these is the crystalline structure of the compound which permits mechanical orientation of the crystals to increase the tensile strength of extruded strips and filaments. It also permits rapid solidifying of thick injection parts by crystallization instead of cooling. The material itself is tough and strong and has good chemical resistance and good electrical properties. It is thermoplastic but has a relatively high softening point of about 250 F. The molding compound may be plasticized to retain any degree of flexibility or rigidity of the molded or extruded part. Saran flexible tubing is an acceptable substitute for rubber in many applications. Extruded strips woven into fabric provide excellent seat and furniture coverings. Rigid Saran pipe has proved satisfactory as a replacement for iron and steel in certain uses. Other trade names are Geon, Plioflex and Velon.

11.12 PROTEIN SUBSTANCES

Protein plastics were among the first to be discovered, but have since seen little development. Casein plastic is pressed from precipitated milk curd to its desired shape and is then hardened in a formalydehyde bath. Practically all casein products are limited to simple shapes that can be fabricated from rod or ribbon, such as buttons and buckles. The material has poor water resistance but is otherwise hard and glossy, and available in all colors. Soybean plastic has found very limited use and is mainly utilized as an extender for phenol formaldehyde resins.

Thermosetting Plastics

11.13 ALKYDS

Alkyd * resins have such a high rate of cure that special rapid-moving presses have been built to handle these molding powders. The alkyds possess excellent dimensional stability, heat resistance, moisture resistance, and arc resistance. The major portion of applications has been in the electrical-insulation field and on large quantities of small parts where maximum value can be obtained from the advantage of the more rapid cure cycle. One trade name is Plaskon.

When properly modified, these resins provide an excellent surface coating (Glyptal) which has a durable glossy film, good adhesion, and is readily applied. They are widely used for automobile finishes, coated fabrics, ordnance paints, aircraft lacquers, and marine paints. Other trade names are Amberlac, Beckosol, and Durycles.

11.14 EPOXIDES

The epoxide † resins have found considerable use as a coating material both alone and in combination with alkyds and urea formaldehyde. As coating materials, they have shown superior toughness, elasticity, and chemical resistance.

These resins have also found considerable use as casting materials and electrical potting compounds. They are transparent light amber color and have very little shrinkage. Inserts may be readily cast in them. As adhesives these materials have shown extremely high bond strengths without the need for pressure for curing. They may be formulated to cure without heat. Aircraft structural members have been bonded with epoxides replacing riveting or welding operations. Trade names are Epon and Araldite.

11.15 FURAN

Furan resins, derived from the basic raw material furfural,‡ can be produced as molding compounds which have good physical and

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* Alkyds are formed by the condensation reaction of a polybasic acid (usually phthalic anhydride) with a polyhydric alcohol (usually glycerin).

† Epoxides, or epoxy resins, are the reaction products of epichlorodyn and bisphenols.

‡ Furfural is prepared from the by-product hulls of rolled oats and cottonseed by subjecting the seed hulls to the action of steam and dilute sulfuric acid in digestion tanks and subsequently distilling the furfural.

electrical properties plus an excellent surface finish. The main use of this type of plastic is as a liquid impregnant to resinify plaster products giving them the appearance and feel of fine ceramic ware and reducing shrinkage to less than 0.001 in. per in. Used as coatings for chemical tanks, they exhibit a high degree of resistance to acids and alkalies and high temperature (350 F). Certain hot-setting coatings possess the same coefficient of expansion as steel and exhibit good adhesion to such surfaces. As adhesives these materials have high bonding strength to thermosetting plastics, vulcanized rubbers, and chemical stoneware with good stability and resistance to aging. In combination with glass-fiber mat the furan resins have been used for corrosion protection of underground gas and oil pipelines as well as porous spacers for storage battery cells. Common trade names are Durisite, Duralon, and Furetone.

11.16 INORGANIC PLASTICS

The adoption of inorganic binders by the plastics industry is largely the result of the search for a material which will withstand high temperatures. Binders for cold-molded refractory compositions include clay, silicates, and Portland cement. Combined with asbestos fillers, they are unaffected by heat as high as 1300 F. These materials can be formed into comparatively fine and delicate parts.

Mycalex is a glasslike plastic, employing a silicate binder which is mica filled. This material can be molded under high heat and pressure. When cooled it becomes hard and smooth finished, with good flexural strength and fair impact strength. It will withstand heat up to 550 F and has good arc resistance and especially low power factor and dielectric loss. These properties make mycalex especially applicable to radio and television parts which are subject to temperatures above the operating temperature of ordinary thermosetting plastics (see Chapter 10).

11.17 MELAMINES

Melamine resins, principally melamine formaldehyde, are thermosetting and are synthesized from calcium carbide and nitrogen. They were first made available commercially in 1939. These resins were developed especially to fill the gap between phenolics and ureas with regard to electrical and physical properties. Melamine resins give a high dielectric strength and high arc resistance in combination with high heat resistance, low water absorption, and general inert-

ness. This makes them particularly applicable to the molding of electrical parts, such as terminal boxes and boards, magnetos, and distributor heads, which are subject to adverse operating conditions. They are also ideal for laminated table-top surfacing, tableware, buttons, lighting fixtures, etc., because they can be made in light colors and will withstand boiling water. The melamine resin is also used for laminating. Trade names are Melmac, Catalin, and Resimene.

11.18 PHENOLICS

The most common of this group and the most used of the thermosetting plastics is phenol formaldehyde,* the resin originally developed by Dr. Baekeland in 1909. They are generally known by the trade names Bakelite, Durez, Resinox, and Textolite.

Phenol formaldehyde compounds are the general purpose materials of the thermosetting plastics. They are comparatively hard, strong, and low in cost, can be molded to close tolerances, and with a good finish, and have all-around electrical, chemical, and thermal properties. By the proper selection of fillers a phenol formaldehyde compound may be made to excel in impact strength (see also Chapter 12 on rubber phenolics), heat resistance, dimensional stability, electrical properties, or some other specific physical property. These compounds are limited in selection of colors to black, brown, green, blue, red, and other dark shades, and to combinations or mottles of them. They have low arc resistance and, unless specially formulated, poor alkali resistance.

The phenolics are available as molding compounds and as resins for laminating and casting. The material is also available as finished laminated sheet, rod, and tube in a wide range of thicknesses and diameters. Typical applications are molded bases, covers (see Fig. 11.1) and operating arms for industrial-control apparatus, bottle caps, handwheels and knobs, camera cases, and terminal boards. Laminated sheets with paper, cotton, or linen filler are widely used for punchings, mechanical applications such as gears, bearings, and

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* Phenol, synthesized from benzene and air or fractionated from coal tar, is reacted with formaldehyde (obtained from the distillation of hard wood or the oxidation of methanol) to produce a fusible and soluble resin. This resin may be dissolved in alcohol to form a varnish which is suitable for coating or for laminating. If the resin is to be compounded, it is allowed to harden, after which it is pulverized, ground, and compounded with the desired filler, dye, plasticizer, and lubricant. This compound is then suitable for molding.
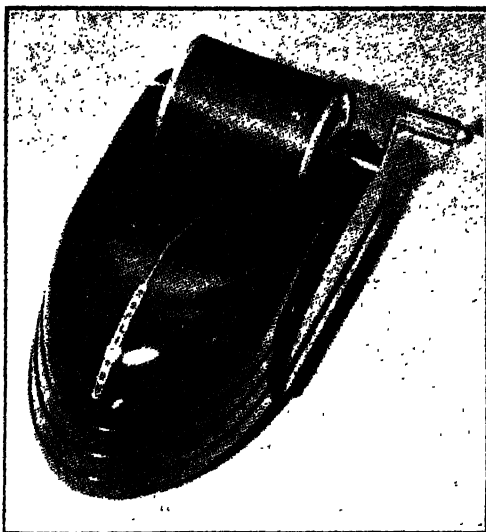
FIG. 11.1.   A compression-molded phenol formaldehyde housing.

cams, and structural applications such as panels, refrigerator inner
doors, tabletops, and rods.

11.19   POLYESTERS

These materials are very similar in chemical composition to the
alkyds, being a reaction product of polyhydric alcohol and a di-
basic acid plus monomer styrene or diallyl phthalate.   In combi-
nation with glass fibers they form a product which has an out-
standing strength-weight ratio.   Added to this are the properties of
hardness, heat and abrasion resistance, unusually high impact re-
sistance, and excellent electrical characteristics which have led to
their use in numerous military applications such as aircraft struc-
tural members, radomes, body armor, skis, and assault landing craft.
The polyesters are liquids that require only contact or low pressure
for laminating and large parts of irregular shape may be formed.
Commercial applications include such items as fishing rods, bread
trays, luggage, washing-machine tubs, chairs, refrigerator parts, sky-
lights, boat hulls, and chemical piping.   High cost of resin and glass
fiber plus problems involved in handling wet materials have been a
deterent to a fuller utilization of the glass fiber reinforced poly-
esters.   Trade names for these materials are Laminac, Paralex,
Permafils (see also Chapter 10), Plaskon, Selectron, and Vibrin.

11.20 SILICONES

Silicones * are plastics that differ radically from the usual materials in that they are based on silicon instead of the usual carbon atoms (see Chapters 9 and 10). The outstanding properties of silicones are high heat resistance, resistance to aging, retention of properties over a wide temperature range, and good electrical characteristics. Silicones may be produced as low viscosity liquids, oils, greases, rubberlike compounds, or resins. Because of the relatively high cost of silicones, their applications have been limited to applications where the maximum use can be made of their unique properties. Applications include water repellents, mold-release agents, hydraulic fluid, gaskets, damping compounds, protective coatings, and adhesives.

11.21 UREAS

Urea formaldehyde † is generally known under the trade names of Beetle and Plaskon. It was developed and put on the market in 1929 in response to the demand for a thermosetting material that could be made in the lighter colors, including white. It is used in the manufacture of such equipment as food scales, dishes, cosmetic containers, and gift boxes where white or an attractive light color is a necessity.

The outstanding characteristic of urea formaldehyde plastics is the wide range of colors and pastel shades. Its mechanical properties slightly exceed those of an equivalent phenolic compound, and its resistance to electric arcs and tracking is greatly superior. Its cost is considerably higher, unless black or brown colors are satisfactory, whereupon a less expensive grade-2 urea compound (woodflour filler) can be used. After urea and also melamine parts are molded, there is apt to be considerable shrinkage (0.005–0.008 in./in.) over a long period of time. This effect can be accelerated by baking the parts after molding. Thin selections of the lighter colors of urea formaldehyde are translucent, and because of this, the material has found wide application in lighting units. A sizeable percentage of urea is used for making buttons and in the electrical

* Basic raw materials are silicon, methyl chloride, and water.

† Urea, synthesized from hydrogen, nitrogen, oxygen, and carbon, is treated with formaldehyde to form the resin. Alpha-cellulose, a pure-white derivative of wood, is commonly used as a filler to complement the color and translucency of the resin.

industry urea formaldehyde is a standby for such things as switch plugs wherever color is desirable. Urea as well as melamines fill an important role as laminating agents, adhesives, and hard-baked enamel coatings.

Methods of Forming Plastic Parts

To achieve a working knowledge of plastics and plastic-parts design, it is necessary to visualize the manufacturing methods and tools used in the plastics industry. For the thermoplastic materials, injection molding, blow molding, extrusion, slush molding, vacuum forming, and foaming techniques are generally employed. For thermosetting plastics, hot-compression molding, transfer molding, laminating, and casting are the most common. These various techniques are almost unique to plastics and give them much versatility.

11.22 INJECTION MOLDING

The process is very similar to die casting. The material enters a heating chamber independent of the mold; as it becomes plastic, a plunger operating at pressures of about 10 tons per sq in. forces
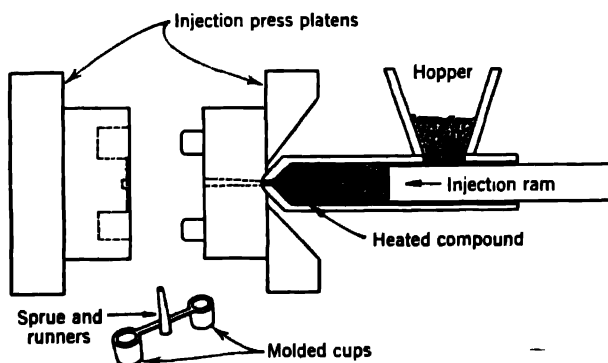
Fig. 11.2. Schematic sketch of the setup for injection molding.

the material through a nozzle into a cooled mold where it solidifies until it is rigid enough to be ejected (see Fig. 11.2). The injection process lends itself to the rapid automatic production of thermoplastic parts and is the most commonly used for rigid thermoplastics. With some materials, particularly clear acrylics, it is necessary to predry the powder before placing it into the heating chamber, since

adsorbed moisture will form small bubbles in the molded part or cause it to become cloudy. Weld or knit lines are sometimes found in injection-molded parts, particularly around inserts or mold pins where the hot plastic moving through the cold mold has chilled suf-
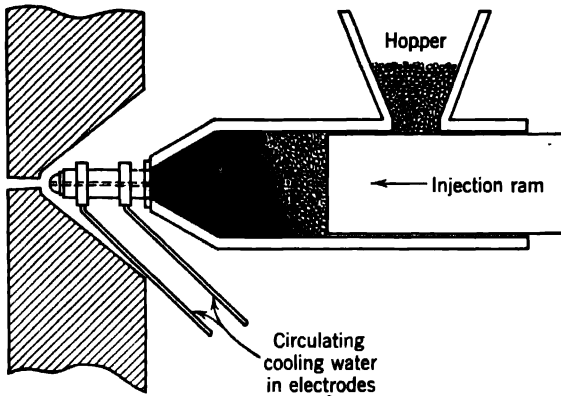
Fig. 11.3.   Schematic sketch of jet molding.
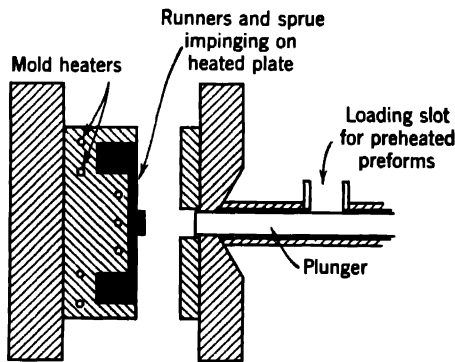
Fig. 11.4.   Schematic sketch of offset molding.

ficiently so that it will no longer form a homogeneous bond with the rest of the plastic in the mold. To overcome this effect and also to prevent the formation of high residual stresses caused by too rapid chilling, most molds are designed with heating and/or cooling coils to maintain controlled temperatures.

Thermosetting plastics may be molded by injection-molding techniques by using certain modifications called *jet molding* (see Fig. 11.3) and *offset molding* (see Fig. 11.4). In jet molding, the ther-

mosetting material is first held in the heating chamber at a moderate heat. As it is forced into the nozzle through which it enters the mold, it is temporarily heated to a high temperature so that it cures very rapidly when it enters the heated mold. Special cooling is necessary to prevent the heat from the nozzle from entering the preheating chamber. This method permits faster molding than does compression molding, avoids preforming, produces parts having excellent surface finish, and allows easy molding of inserts. Offset molding operates on the same principle as jet molding, i.e., rapid heating of the material to curing temperature just prior to entering the mold, but the warmed resin impinges on a hot plate on leaving the nozzle and is forced sidewise into the mold cavities.

Both jet and offset molding offer the advantage of speed over compression and transfer molding but the greater control over temperature required and the liability of jamming of the machine, which could easily result from a momentary failure of the controls, makes these methods more hazardous.

11.23 HOT-COMPRESSION MOLDING

Hot-compression molding is the most commonly used method of shaping a thermosetting plastic to some desired form. The plastic compound, in the form of powder, granules, or preformed briquettes,
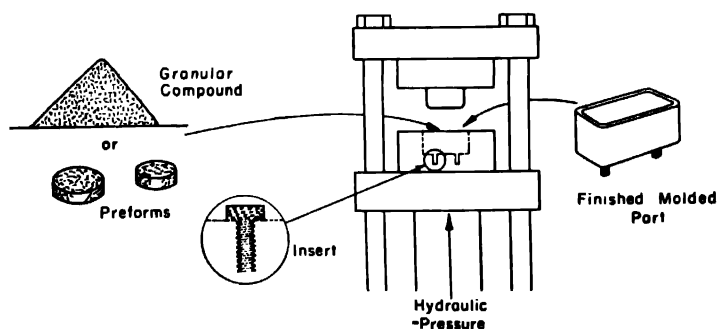
FIG. 11.5. Schematic sketch showing the steps in the hot-compression molding of a small part containing two inserts.

is loaded into the heated mold cavity (see Fig. 11.5). As the mold closes under pressure, the compound becomes semifluid and fills the mold shape. The mold cavity and plunger are split at a convenient parting line so that the finished part may be ejected. All sections of the mold which form the part are of hardened steel and usually

chrome plated to withstand the high pressure and abrasion. They are heated to a temperature of approximately 350 F, and pressures of 2000 to 10,000 lb per sq in. on the molding material are necessary to form the part. The material is then held in the mold until the resin has polymerized and become infusible. The length of time of this *cure* varies chiefly with the thickness of section and will
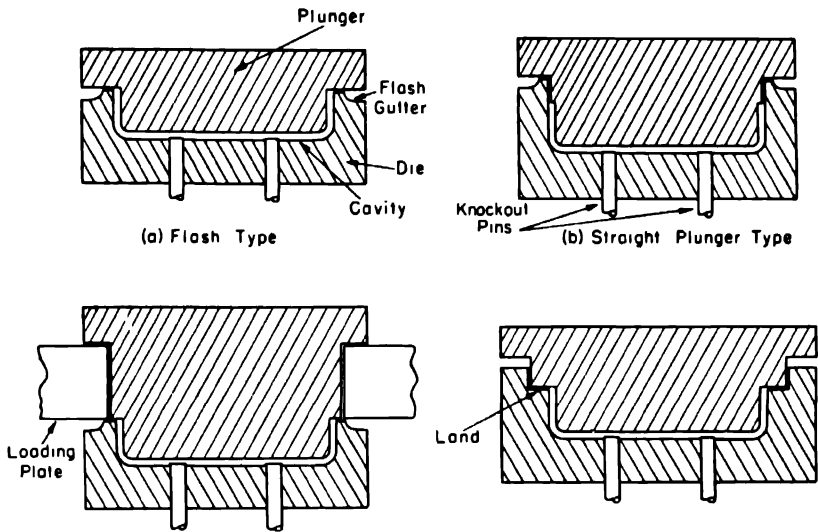
Fig. 11.6.   Sketches illustrating the common designs of compression molds.

usually take about 1 min for a section of $\frac{1}{8}$ in., with increasingly longer cures for thicker sections. After the part has cured and become rigid, it can be ejected from the mold while still hot.

The method of sealing off the compound and providing a cutoff at the line at which the cavity and the plunger come in contact leads to various designs, the most common of which are shown in Fig. 11.6. The proper type of cutoff is assigned to the mold by the mold designer.

The method of assembling the cavity and plunger into a frame is shown in the sketch in Fig. 11.5, which illustrates the construction for a typical small single-cavity landed-plunger compression mold. Provisions are made for ejecting the molded part when the dies are separated. Fig. 11.7 is a photograph of a two-cavity compression mold.

Heatrionic, or high-frequency, heating provides a method of heating these plastic materials, which are basically heat insulators, quickly and uniformly to molding temperatures. Ovens, hot plates, and heat lamps are also commonly employed to preheat the mold-
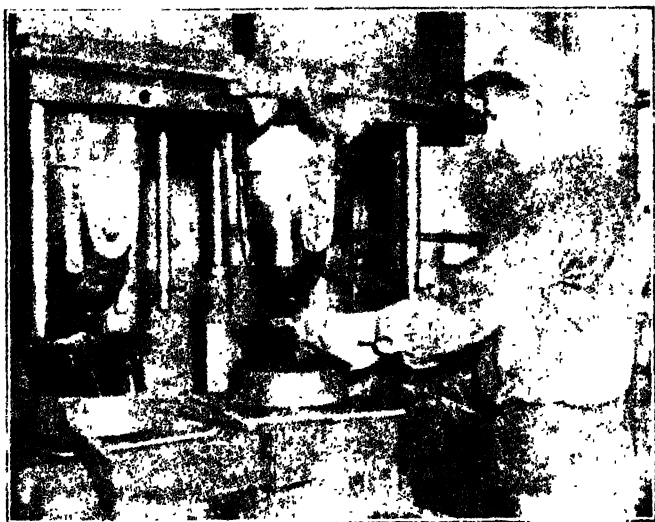
FIG. 11.7. A large two-cavity compression mold.

ing compounds. This reduces the cure time, allows uniform curing of thick and thin sections, allows lower molding pressures which in turn permit molding around more delicate inserts, and reduces mold abrasion. Harder, less expensive materials can be molded and less costly molds can be used because of the increased number of parts which can be produced per mold.

11.24 TRANSFER MOLDING

Transfer molding employs the same materials and the same mold cavity as a compression mold. But it differs in this respect: in a compression mold, the molding compound is loaded directly into the molding space and, as the mold closes, the material is displaced under high pressure and with considerable turbulence; in a transfer mold, the molding compound is loaded into a separate pot or well and, as the mold closes, a close-fitting plunger causes the compound to flow from the well through a sprue and into the mold cavity (see Fig. 11.8). Some transfer molds operate without the use of an auxiliary plunger where the closing of the mold causes the ma-

terial to flow from the well into the cavities—this is called conventional transfer molding as opposed to the first type, which is known as plunger transfer molding. Thus, no appreciable pressure is exerted on the mold cavity until the cavity is completely filled and the fluid pressure is transmitted.

This absence of undue mold pressure is the outstanding advantage of transfer molding. It allows the use of molds with delicate mold sections and use of fragile and weak inserts. Other advantages of the transfer mold are a better and faster heat transfer to
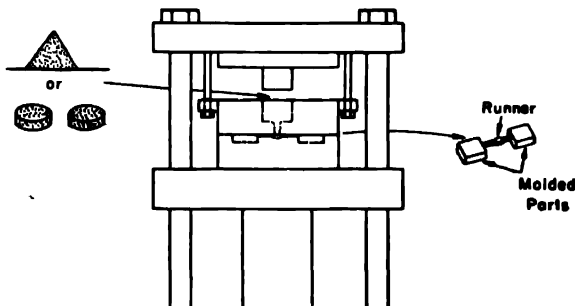
Fig. 11.8. Schematic sketch showing the steps in transfer molding.

the compound as it flows through the sprue, decreased cleaning through the elimination of build-up flash, and better molding tolerances.

Utilization of high-frequency heating of the preforms eliminates the need for heating the chamber, or "pot," of the transfer molding equipment, and allows the use of smaller gates into the cavities wherein the frictional heat permits more rapid cure of the material in the cavity.

11.25 EXTRUSION

The extrusion of plastics is a means of molding a part of constant cross section and continuous length. Material is heated to a plastic state in a cylinder; it is then forced from the chamber by a revolving screw through an orifice of the desired shape (see Fig. 11.9). As it leaves the orifice it is chilled by an air blast and is supported and removed by a long conveyor belt. At the end of the conveyor, the solidified material is wound on rolls or cut to convenient lengths. The final shape of the cross section is affected by the operating conditions of the machine. For example, it is
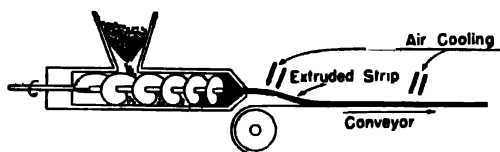
Fig. 11.9. Schematic sketch showing the extrusion of a plastic strip.

possible to stretch or compress the shape of the extrusion from any one die by adjusting conveyor speed.

11.26 LAMINATING

A laminated material is composed of a stack of fibrous or porous sheets impregnated or coated with resin and bonded together by heat and pressure to form an integral body. Laminates are divided into groups according to the pressure required to cure the resin in manufacture. Laminates cured at pressures above 1000 lb psi (usually 1200–2000 lb psi used) are referred to as "high-pressure laminates." Those cured at pressures below 400 lb psi are called "low-pressure laminates." Those laminates curing at 0 to 25 lb psi, i.e., polyesters, are sometimes referred to as "contact-pressure laminates."

High-Pressure Laminates. In high-pressure laminates the resins most commonly used are phenolics, melamines, ureas, and silicones. Since the filler is usually in sheet form, laminated shapes are confined to flat sheets, tubes, rods, and relatively simple molded parts such as refrigerator inner doors. When forming sheets, the requisite weight for the desired thickness is stacked up, placed between two finished steel pans, and pressed between heated plates in a hydraulic press (see Figs. 11.10 and 11.11). Tubes may be either molded or rolled. For molded tubes the paper or fabric is rolled on a steel mandrel of the desired diameter and then placed within a steel mold for the final processing (see Fig. 11.12). For rolled tubes the mandrel is heated, the paper or fabric is highly-compressed by other heated rolls and the processing takes place as the mandrel is revolved, final curing being done by subsequent heat treatment. In the manufacture of rods, the paper or fabric is rolled on a mandrel of very small diameter, which is withdrawn before the material is placed in the mold.

Cotton cloth and paper laminates are most common, but laminates of asbestos paper, of cloth, and of glass fabric are also available. Heavy cloth laminates of cotton duck or linen are used for
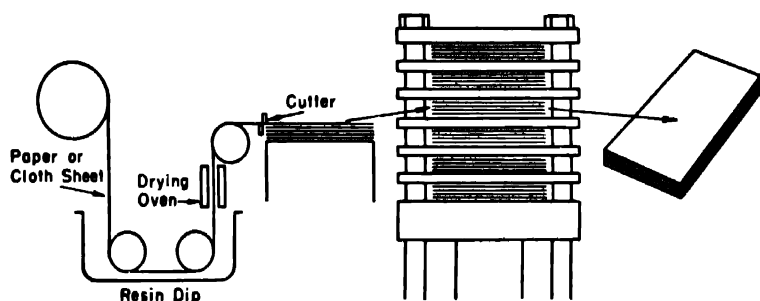
FIG. 11 10. Schematic sketch showing the steps in laminating sheets.
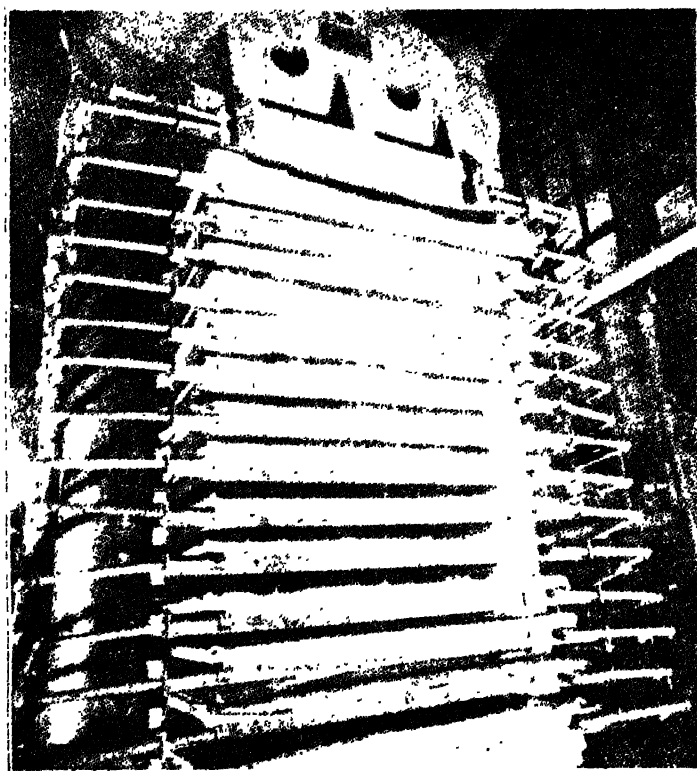
FIG. 11.11. Fifteen laminated canvas sheets ready for pressing in a hydraulic press.

gear blanks, cams, and other industrial applications. Paper laminates are used principally for electrical insulation and punch-stock material. Decorative laminates with figured or colored faces are available and are used extensively for tabletops and wall facings. Vulcanized fiber is a form of laminate.

Postforming can be employed with certain grades of phenolic laminates. This consists of heating the laminate to 300 F or above for short periods and then forming to many useful contours or shapes, using pressures as low as 5 lb psi and seldom exceeding 100 lb psi,
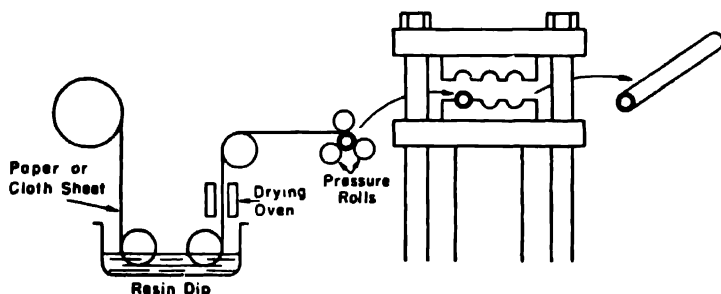
FIG. 11.12. Schematic sketch of the steps in laminating rods and tubes.

without loss of properties of the original sheet. This permits large structures to be molded from long lengths of continuous sheet with inexpensive molding equipment and tools.

Low-Pressure Laminates. The development of low pressure laminating has centered principally around plywood and glass-reinforced polyester parts. Considerable investigation has also been made into sandwich-type construction involving the use of foam, honeycombed resin-bonded paper, or balsa wood which give superior strength-weight constructions.

Many polyester laminates may be formed by contact pressure by merely forming the fiber-saturated material on a mold and curing with heat, catalysts, or sunlight. For slightly higher pressures a thin flexible bag of Cellophane plus vacuum pressure may be used. For greater pressures the part may be encased in a flexible rubber bag and placed in an autoclave using live steam (see Fig. 11.13), or the resin-treated layers may be placed in a female mold and pressure applied with a flexible rubber bag. To achieve the optimum in surface finish, matched metal dies with positive cutoff may be employed.
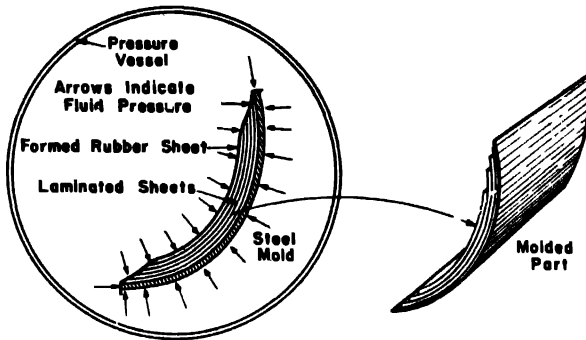
FIG. 11.13. Schematic sketch showing the method of low pressure laminating plastic parts.

11.27 BLOW MOLDING

This technique applies only to thermoplastics and is used principally to produce hollow articles such as bottles and floatable objects. Two methods are employed, the direct and the indirect. The direct method consists of injection molding or extruding a measured amount of material in the form of a tube, sealing off one end of the tube, placing a split blow cavity around the hot plastic, and blowing air into the tube to expand it to the walls of the cavity (see Fig. 11.15). Indirect molding consists of a flat sheet, which has been uniformly softened by heat, being clamped at the edge between a die and a cover. Air applied between the sheet and the cover forces the sheet into the shape of a hemisphere or whatever the configuration of the mold may be. Parts produced by the indirect method have excellent appearance but are more costly because of the utilization of only about 50 per cent of the sheet stock. Also there is a tendency for excessive thinning of the sheet at the deepest point of the draw (see Fig. 11.16).

Another use of blow molding is to expand a tube until its walls are reduced to very thin film thicknesses. This is done by injecting air inside a tube of a material such as polyethylene at it leaves an extrusion die. The method provides an inexpensive, flexible, easily controlled means of producing films which in some cases are thinner than could be produced by any other method (see Fig. 11.17).

11.28 VACUUM FORMING

This method is very similar to indirect blow molding. The sheet stock is clamped at the edges over a box structure which has a
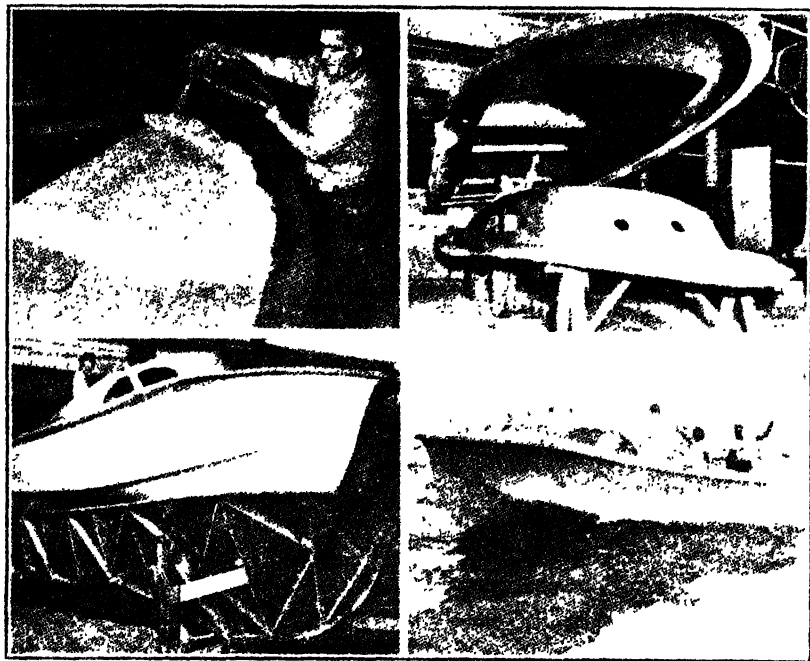
FIG. 11.14. A boat hull fabricated by low-pressure laminating. In the mass-production boat-building operation shown above, female hull and deck molds, which have been lubricated for separation, are used. Surface coats of Laminac Resin, pigmented to the desired color, are sprayed into the molds, followed by the laying up of Fiberglas reinforcing mat sections which have been trimmed to shape. Additional resin is used to impregnate the mat. Hull and deck then are brought together and cured under heat to form a seamless, one-piece unit.

(a) Sealed tube extruded into open mold

(b) Mold closed—tube expanding under air pressure

(c) Tube fully expanded and sealed into mold
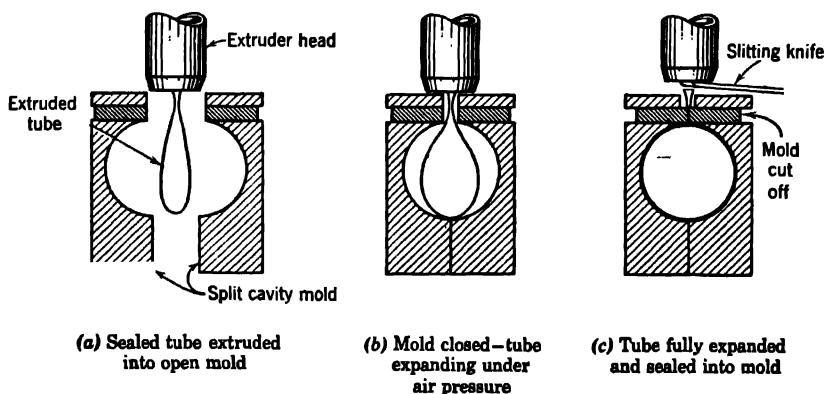
FIG. 11.15. Schematic sketch illustrating direct blow molding.
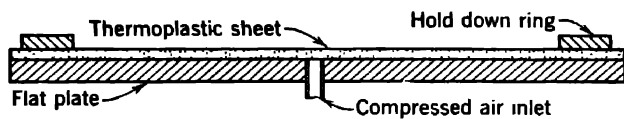
(a) Sheet in place ready for heating
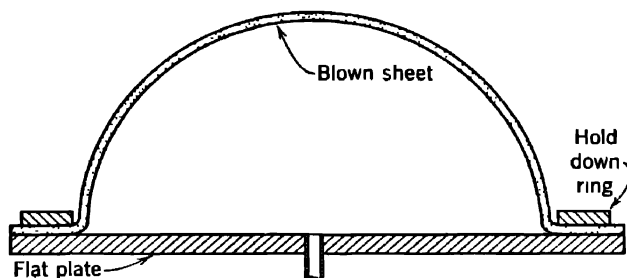
(b) Heated sheet blown to desired size

FIG. 11.16   Schematic sketch illustrating indirect blow molding.
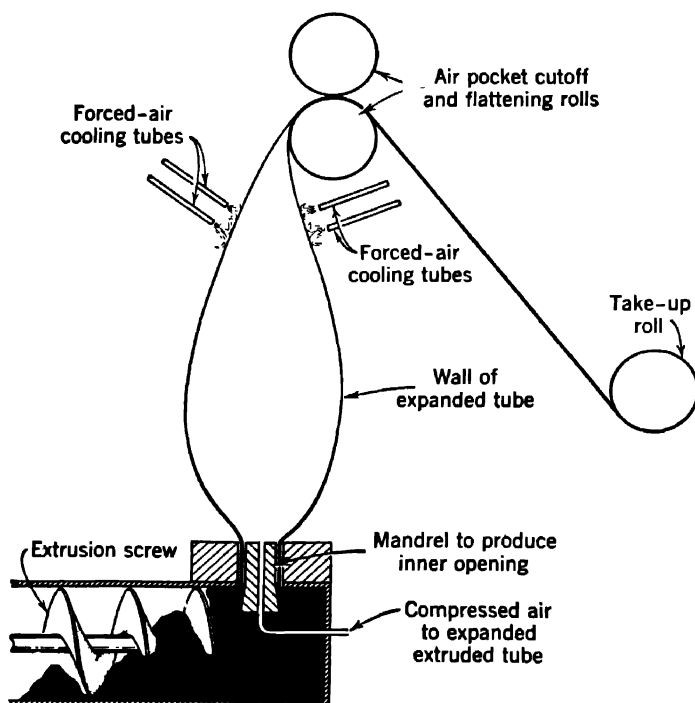
FIG. 11.17.   Schematic sketch of a blow-molded film.

wire screen bottom supporting the male or female mold (see Fig. 11.18). The sheet is uniformly heated and a vacuum which has previously been created in an accumulator tank is applied to the bottom of the screen, drawing the heated plastic into the contours of the mold with a "snap" action. The advantage of this method is in the production of large areas of thin section, which would be impossible to mold by injection-molding methods, plus the use of low-cost dies and equipment.

11.29 SLUSH MOLDING

Slush molding in plastics is essentially the same as slush molding in metal. The liquid material is poured into a hollow mold, slushed around to provide an even coating inside the mold, and, after some solidification on the inside walls of the mold to the desired thickness, the excess material is poured out. The basic difference with plastics is that the plastic enters as a cold liquid and is solidified by the use of an accelerator and heat (in the case of thermosetting compounds) or by heat alone (in the case oi plastisols). Plastisols are the principal materials employing the slush-molding technique because of their flexibility and toughness, which permits them to be withdrawn from undercuts in the mold. Parts produced in this manner have infinite detail, extreme accuracy, and are of very low cost.

11.30 FOAMED OR EXPANDED PLASTICS

Foam plastics have found use as floatation material, shock-resistant mountings, packaging material, and thermal insulation. In general, the methods employed to produce an expanded plastic are: (1) a low viscosity plastic is mechanically agitated, with or without foaming agents, and solidified; (2) the plastic substance in a doughlike condition is expanded by a blowing agent uniformly distributed throughout the mass; (3) a gas, or mixture of gases, is dissolved in the soft plastic mass under relatively high pressure and upon release of pressure, expands the mass whereupon hardening fixes the porous structure; (4) a soluble solid is incorporated in the plastic material and leached out after the mass is molded; (5) a fibrous or other bulky constituent is mixed with a binding substance to produce a porous product.
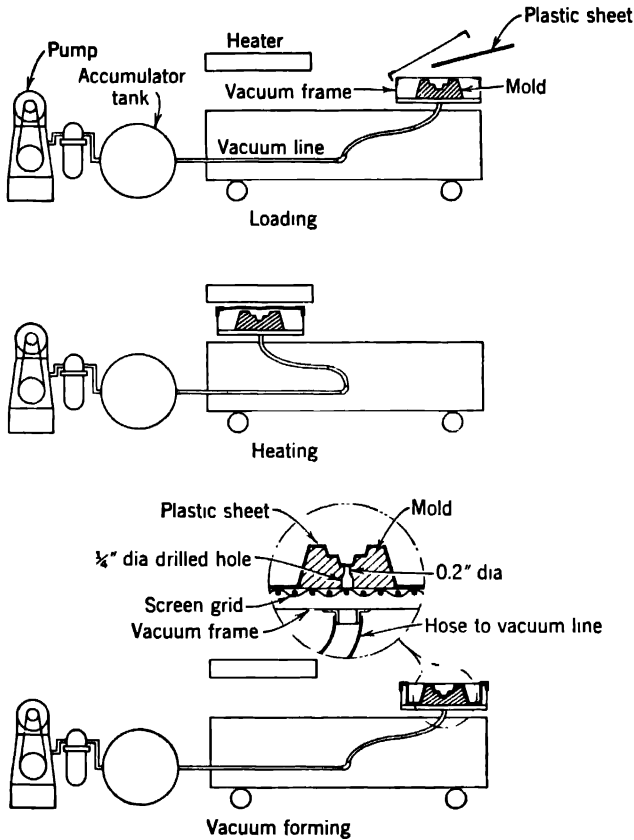
Forming polystyrene sheet by vacuum drawing

Fig. 11.18. Schematic sketch of vacuum forming.

11.31 COLD MOLDING

Cold molding is a forming process in which a molding compound is pressed or cold formed to shape and then baked to achieve its final properties (see Fig. 11.19). Since the part is not cured under pressure and since cold-molding compounds are rather coarse, the appearance of the finished part is not as pleasing as that of hot-molded phenolics.

Molds for cold molding are usually of the straight plunger type. They are not equipped with heating channels and quite often are single-cavity molds because of the poor flow of cold molding compounds. The abrasive action of the compound causes a high rate

of mold wear. In the pressing operation, the mold cavity is filled with compound, usually of the nonrefractory type, and the mold is closed quickly and forcefully. The compound may then be further

Molding Powder To Be Baked
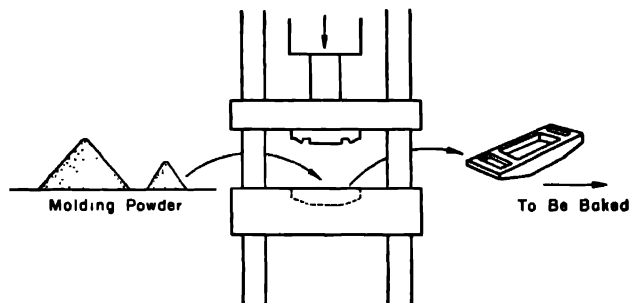
FIG. 11.19. Schematic sketch of cold-molding process.

sized by opening and closing the press several times. The molded part is then removed from the cavity and placed on a tray, which is placed in an oven. The parts are baked for 1 to 3 days at temperatures to 425 F. In processing refractory-type cold-molded compounds, the parts are baked at higher temperatures to set the binder.

11.32 CASTING

By a variation in the method of manufacture, some very clear viscous resins can be produced which will harden when baked at a moderate temperature. Since no pressure is necessary to cause such a resin to fill a mold, very inexpensive and light molds may be used. This is the principal advantage of the use of cast plastics. Since they contain no filler, they have an unrivaled deep lustrous finish, available in any color or variegation.

Parts to be made must be of a fairly simple shape and have a broad dimensional tolerance. A steel mandrel is made to the outside shape of the part and is dipped into a lead bath until the film of lead can be stripped from the mandrel and is rigid enough to serve as the mold for the casting. If the part is to be cored out, lead cores are made in a similar manner. The shells are then filled with resin and the resin is cured in an oven or with catalysts. These operations are shown schematically in Fig. 11.20. Finished parts such as chess and checker men, jewelry, sheets, rods, and tubes for machining are made in this manner.
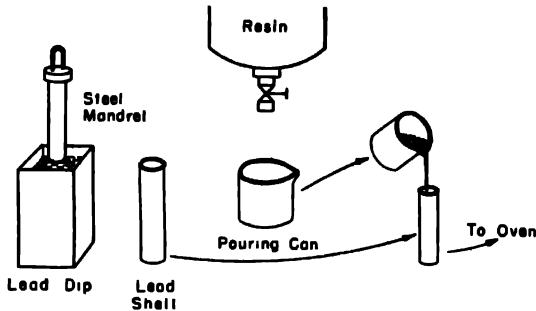
FIG. 11.20. Schematic sketch of casting process.

Part Design

11.33 MAIN CONSIDERATIONS

The design of plastic parts involves three major considerations: (1) the selection of the proper material to give the desired properties, (2) the selection of a means of fabrication which is suitable and economical, and (3) the proper part design to enhance the material properties and to facilitate manufacture.

Since these considerations often involve the work of more than one department, there should be at all times close cooperation between all parties concerned. The engineer and the draftsman should indicate all technical details and various mechanical and functional factors that must be considered. The artist may lend his talents to creating a design and style that will be pleasing from the consumer's point of view and will employ color in keeping with the trend of the times. The molder can assist in selecting the plastic that will be most satisfactory and may suggest changes that will improve the part or make it more economical to produce.

There are many interrelated factors affecting the design, and the proper incorporation of these factors calls for a high degree of skill and experience. The use to be made of the product will require certain appearance and certain properties in the plastic from which it is to be made. Each plastic has particular forming techniques that will have an important bearing on the design. Additional factors are the size and shape of the product, and the estimated production.

For molded parts a single-cavity sample mold should first be produced to make the article itself of the chosen plastic. This

permits accurate determination of such important characteristics as shrinkage, assembly, and serviceability before production tools are made.

Precautions should be taken to determine that the product is designed correctly in every detail before a mold is built. One cannot be too careful to avoid that overconfidence so often found in designers or customers who believe that their designs on paper are perfect and, therefore, will not produce models or a single-cavity mold but proceed with production molds immediately. Experience has proved that when molds are completed and the designer sees the actual part, he often finds that several changes must be made. With a model or a single-cavity sample mold, changes can be made quickly and with little expense. Changes in production molds are expensive and involve considerable danger of ruining the molds.

Almost any part can be molded at a price. However, the customer usually wants economical production. Definite restrictions are therefore imposed on the design of molded parts and the molds to produce them. These restrictions are constantly changing as new materials or new methods are found to eliminate or reduce them.

11.34 SELECTION OF THE PROPER MATERIAL

Although the various classes of molding compounds have been discussed, it has been difficult to compare them on general terms. In selecting a material for a given application, certain desired physical properties will be the basis of selection. The more important physical properties of the common plastics are compared in Table 11.2.

In using these data or other references, it must be remembered that most compounds have a wide range of formulations. This range and the variability introduced by molding operations result in improvement in some properties at a sacrifice in others. Hence, do not assume that the upper values of several properties will hold for a given compound. The manufacturer of materials, the laboratory plastics engineer, or the molder should be consulted in such a matter.

The designer must further consider the operating conditions to which the plastic will be exposed. The physical properties and the operating characteristics of the part will be greatly affected by conditions such as humidity, heat, and sunlight, and allowances must be made for them. Parts to be subjected to intense heat or

Table 11.2 Physical Properties of Common Plastics

	Specific Gravity	Tensile Strength, 1000 lb/sq in.	Notch Impact Strength, Izod ft-lb/in. notch	Modulus of Elasticity, 10^6 lb/sq in.	Thermal Expansion, $10^{-6}/°C$	Maximum Operating Temp., °F	Dielectric Strength, VPM step by step, 100 C	Dielectric Constant, 10^6 cy	Power Factor, 10^6 cy	Water Absorption, 24 hr, %
Alkyds	2.18–2.22	..	0.18	2.5	3.5	350–400	325–335	6.9	0.018	0.11
Aniline	1.2–1.25	8.5–10	0.3	0.45–0.6	5–6	180–200	..	3.6–3.8	0.006–0.008	7–14
Casein	1.35	10	1.0	0.51–0.57	4.1–6.8	275	350–500	6.1–6.8	0.052	..
Cast phenolic unfilled	1.25–1.35	8.5–10	0.5–0.7	0.4	7–11	160–170	..	7.4	0.02–0.05	0.4–0.6
Cellulose acetate	1.1–1.2	3.5–10	0.75–4	0.1–0.4	8–16	140–230	200–300 *	3.3–6.3	0.01–0.06	0.2–4.7
Cellulose acetate butyrate	1.3–1.38	2.5–8	0.8–5.5	0.1–0.4	11–16	140–230	..	3.3–6.3	0.01–0.05	1.6–2.2
Cellulose nitrate	1.35–1.40	5–12	2.0–8.0	0.2–0.4	12–16	135–150	..	6.3	0.07–0.1	0.6–2
Cold molded:										
Nonrefractory	1.87–2.15	..	0.4	..	..	500	..	..	..	0.7–3
Refractory	1.80–1.90	1.2	0.4	..	..	1300	..	6	0.07	0.6–15
Epoxides	1.11–1.23	2.0–8.0	0.5–1.7	0.45	6	300	380	3.6	0.019	0.14
Ethylcellulose	1.09–1.17	1.8	3.0–11.0	0.1–0.3	10–20	115–185	300–530	2.8–3.9	0.01–0.06	0.8–1.8
Fluorocarbons	2.1–2.3	3.0–4.5	2.4–4.5	0.058	10	400	430	2.0	0.0002	0.00
Furan	1.75	4.2–10	..	0.8	..	265–330	..	..	..	0.01–0.2
Hard rubber	1.1–1.76	4–7	0.5–0.55	0.5	7	210–225	340–360	3	0.003–0.008	0.2
Melamine, cellulose filled	1.45–1.47	10.9	0.25	..	8–9	120–145	470–510 *	2.7–3.5	0.014–0.03	1–1.7
Methacrylate	1.15–1.18	7–12.2	0.2–0.4	0.4	10	300	340	3.4	0.04	0.4–0.6
Nylon	1.14	5.5–8	1.5	..	..	250–265	..	4.4–5	0.014–0.041	1.5
Phenol formaldehyde:										
Wood-flour filled	1.22–1.48	4.5–8	0.2–0.4	0.7–1.0	2–6	250–265	60–100	4.5–8	0.035–0.1	0.25
Asbestos filled	1.6–2.1	5.5–7	0.2–0.4	1.0–1.5	4–7.5	380–390	60–75	4.5–20	0.005–0.1	0.2–0.7
Cotton-flock filled	1.32–1.38	5.5–8	0.2–0.7	1.04–4.5	2–4.5	230–245	50–70	4.5–6	0.04–0.1	0.1–0.3
Rag filled	1.32–1.38	3.5–9.0	0.3–0.7	0.7–1.1	2–6	230–245	40–60	4.5–6	0.04–0.1	0.6–2.3
Polyesters (rigid)	1.10–1.46	..	0.85–4.8	0.7–1.2	8–10	212	280–420	2.8–3.7	0.009–0.026	0.15–0.60
Polyethylene	0.92	1.3	0.3–0.4	0.3–0.5	16–18	250	420	2.3	0.0005	0.01
Polystyrene	1.05	5–9	3	0.019	6–8	146–190	440–540 *	2.5–2.7	0.002	0.2
Polyvinyl chloride	1.2–1.6	1.0–9.0	0.3–0.5	0.2–0.5	..	150–175	300–400 *	3.3–3.5	0.09–0.1	0.1–0.6
Polyvinylidene chloride	1.65–1.72	3.0–5.0	0.30–1.0	0.05–0.08	0.3–1.0	160–200	300	3.0–4.0	0.045–0.065	0.1
Shellac	1.1–2.7	0.9–2.0	2.6–2.9	0.5–0.6	..	150–190	150	3.7	0.09	0.07
Silicones (glass-fiber filled)	1.7	2.8–3.4	4.0–4.5	..	2–3	480	95–115	..	0.0017	1–3
Urea formaldehyde	1.41–1.49	5–8.5	0.2	1.2–1.5	..	163–175	370–400 *	6.6–7.8	0.028–0.036	0.2–0.3
Vinyl chloride acetate (rigid)	1.33	8–10	0.4–1.2	0.35–0.45	7	130–140	..	3.2	0.13	0.2–0.3

* Dielectric strength at 25 C.

Table 11.3   Comparison of Methods of Forming Plastics

Forms	Cast	Hot Molded			Extruded	Cold Molded	Laminated	Vacuum Formed
		Compression	Injection	Transfer				
Forms	Sheets, rods, tubes, simple shapes subsequently machined to finished size	Intricate shapes			Rods, tubes, simple shapes, subsequently machined to finished size	Moderately intricate shapes	Sheets, rods, subtubes, subsequently machined to finished size simple shapes of uniform selection	Shapes from sheets
Choice of materials	Few	Widest choice	Only thermoplastics	Widest choice	Only thermoplastics	Few	Fair choice	Only thermoplastics
Finish	Very good	Good to very good			Good	Fair	Fair to very good	Fair
Metal inserts	Yes	Yes	Yes	Yes	No	Yes	Occasionally	Yes
Accuracy of dimension	Poor	Good	Very good	Very good	Fair	Fair	Fair to good	Fair to good
Mold cavities	Single	Multiple	Multiple	Multiple	Single die	Usually single	Multiple	Usually single
Mold cost per cavity	Very low	High	Highest	High	Low	High	High	Low
Production per cavity per unit time	1 Casting	Medium	High	Medium	High	High	Low	Low

fire will give the best service if made from flame-resistant material. Allowance must be made for heat, humidity, and dust, and arcing in the design of electrical apparatus. Failure is frequently a result of a conducting track of dust, moisture, or an arced-over surface. Weathering will affect color, finish, and transparency of plastic parts; sunlight may fade or darken the color.

The problem of cost must always be taken into consideration in the selection of a material. Often a material with the most desirable propreties will be too expensive for the application and a lesser quality material, which will nevertheless meet the requirements, must be chosen in order to have a competitive marketable product.

11.35 SELECTION OF ECONOMICAL PROCESS

This choice is rarely a matter of great question once the material has been decided upon. For any given material and part shape there is usually one means of fabrication that appears best. The difficult decisions arise, however, when the material selection is not unique, that is, when several different methods of fabrication, each with a different material, could be used. In general, the methods of forming compare as indicated in Table 11.3.

Sometimes it may be better to change a complicated design or a heavy section, such as a ball, to two or more simple moldings and assemble them (see Fig. 11.21). Thermosetting or thermoplastic compounds may be cemented together to form a reliable and watertight seal. Thermosetting compounds are usually bonded under pressure and baked. Thermoplastics can usually be cold joined with a solvent such as acetone. For solvent-resistant thermoplastics like polyethylene, hot-gas welding is often employed as a means of joining.

FIG. 11.21. Cross section of a ball molded in two parts to eliminate heavy sections.

Threaded inserts should be used for parts that may be frequently disassembled, for partial assemblies, for parts requiring adjustments, and for good strength. To avoid the cost of a molded insert, it is becoming a common practice to mold a hole and then stake, snap, or otherwise lock an assembled insert in place. Self-threading screws

should be used for economy, moderate strength, and infrequent disassembly. Drive screws are best for long holes and for permanent assembly. Inserts with a spin-down collar and female threads provide rivet and screw connections and are very convenient. Rivet inserts may be spun down but should not be hammered down.

When considering assembly, all rigid mountings should be studied. Differences in the thermal expansion of metal and plastic, or in the aging of dissimilar plastics, may cause cracking if restrained by rigid mountings.

11.36 DESIGN OF THE PART

In a design involving calculation of mechanical stresses, the factors of fatigue, cold flow, and temperature must be considered. It is recommended that a safety factor of 4 over the short-time tensile strengths be used for parts to be subjected to 1 million fatigue cycles. A factor of 8 should be used for sharply notched parts. Impact strengths will be similarly affected and, for 200,000 impacts, the strength may be only 30 per cent of the single-blow impact strength. Thermoplastics are rather susceptible to cold flow, but thermosets, like phenolics and urea, are little affected. The tensile strength of phenolic materials decreases with an increase in temperature, whereas the impact strength is at its best between 100 and 160 C, and decreases rapidly above and below those temperatures. Tensile strengths of most thermoplastics drop rapidly at very moderate temperatures such as 100 F. Impact strengths of some thermoplastics decrease greatly at subzero temperatures.

In designing for molding, the first thing to be remembered is to design the part so that it can be removed easily from the mold. When this point is overlooked, the molds are impractical for quantity production. Proper design and simplicity of the part will result in simplicity in the design of the molds to be produced. The more complicated the molds, the more expensive will be the production costs. Do not assume from this, however, that complicated and intricate pieces cannot be produced. They can be and are being turned out regularly, but the mold costs and production costs are commensurate with their complexity. Regardless of the intricacy of a molded part, there are certain basic design factors which should be followed.

(1) There should be no radii at corners on the parting line.

(2) Adequate surfaces or bosses for the knockout pins should be incorporated in the design and indicated on the drawings.

(3) Avoid molded parts which necessitate delicate mold sections.

(4) Avoid as much machining of the finished part as possible. Drilling, tapping, grinding, and machining of undercuts are frequently justified, but machined surfaces are more susceptible to wear and to absorption of moisture.

(5) Internal undercuts are difficult to mold, and it is usually better to divide the part and make two sections which can be assembled into a unit after molding.

11.37   RADII, FILLETS, TAPER, AND RIBS

Radii and fillets on molded parts reduce chipping, simplify machining of molds, assist flow of compound, improve appearance, and add strength. A radius of 0.010 in. is very small but sufficient to break a sharp corner; a 0.020-in. radius is slightly rounded and just noticeable; a 0.030-in. radius or larger is most beneficial. Sharp
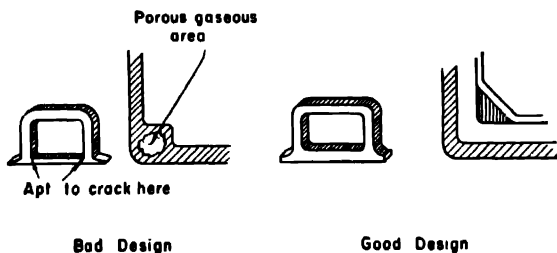
FIG. 11.22. Sketch illustrating good and bad design of a small part and a corner Note that generous fillets are preferred and that abrupt changes in section should be avoided.

corners, therefore, should be avoided unless located at the cutoff (parting line) or produced in a mold built from sections. Fig. 11.22 illustrates the use of fillets to provide gradual changes in section.

Pins, wedges, and threaded plugs that must be removed from the mold during the molding cycle are likely to become nicked and rounded over. If possible, provide fillets and grooves in the molded part to allow ends of pins and wedges to become rounded over, or to allow shoulders on the tools to absorb abuse (see Fig. 11.23).

Molded parts can be made with no taper if necessary, but they may show score marks on the sides. On long draws tapers as low

as 0.001 in. per in. have been obtained satisfactorily. It is better, however, to provide an average taper of one degree or 0.016 in. per in. for general work (see Fig. 11.23). One-half degree, or 0.008 in. per in., is allowable where needed. Three to five degrees should be provided for deep barriers or bosses. It should be stated on the drawing whether the taper is to be taken large or small from the drawing dimension. If no taper is allowed, state this definitely on the drawing, otherwise the molder will provide maximum taper to simplify molding.
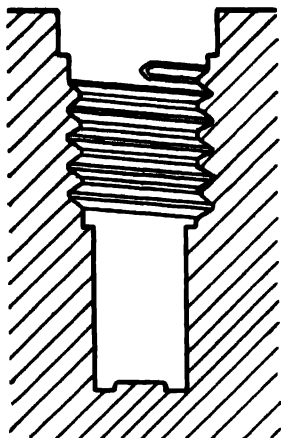
Fig. 11.23. Design of internal thread which provides for wear and rounding of thread plug.

Ribs not only provide strength but also serve as runners facilitating the molding of injection and transfer molded parts. Width of the rib should be at least one-half the wall thickness. Deep barriers and fins should be avoided since they require difficult mold work.

11.38 WALL THICKNESS AND CROSS SECTION

Wall thickness should generally be limited to the following:

	Inches
Phenolic Parts	
Minimum	0.025
Small parts	⅟₁₆
Average	³⁄₃₂
Large parts	¼
Practical maximum	1
Translucent Urea Light Fixtures	
Minimum	0.035
Average	0.050
Maximum	0.125
Injection Molded	
Preferable thickness	0.050 to 0.125

Wherever possible, the thickness of walls should be uniform. Abrupt junctions of thick and thin sections should be avoided. Cross sections with abrupt changes may cause parts to crack after molding because of the strains set up by uneven cooling. It is a good practice to hold variations in cross section to less than 3:1.

Shrink marks are often caused by heavy sections, particularly when molding thermoplastics. They can usually be eliminated by coring out the heavy sections. With thermosets, the cure time depends on the thickest section. Local thick sections thus increase molding

FIG. 11.24. A molded part for electrical-control equipment. Note the generous use of fillets and tapers.

costs. With thermoplastics, local thick sections will require increased pressing cycle time, which will also mean increased molding cost.

Thin walls require less material, less molding time, and are more economical up to the point where breakage and chipping occur. Sharp, delicate edges chip easily. Thin bosses and projections should be less than twice as long as they are thick. Thin walls may be reinforced with ribs. Thin uniform walls are especially important for urea molding because the ureas are sensitive to gas marks, poor knitting, and shrinkage cracks.

11.39 HOLES AND BOSSES

Molded holes are formed by steel mold pins. As these pins are subject to breakage in bending, they must not exceed certain limits of slenderness. The ratio of length to diameter should be limited to these values.

Type of Mold	Pin Support	Slenderness Ratio
Compression	One end	2:1
	Two ends	6:1
Transfer	One end	6:1
	Two ends	15:1

The slenderness of pins $\frac{1}{16}$ in. or under, supported at one end only, should not exceed 1:1 in a compression mold. Where a hole is to be molded with two butt pins, one pin should be at least 0.020 in. larger than the other to compensate for mold misalignment.

Molded countersunk flathead screws should have the countersink slightly depressed into the part. If butt pins are used for molding the hole they should not be butted at the base of the countersink. Countersunk holes should be used for holes to be tapped after molding or for holes for self-threading screws.

Side or oblique holes are difficult to mold. It is frequently easier to drill such holes with the aid of drill jigs. Long holes of small diameter may be spotted and then drilled after molding. Side holes may sometimes be produced by the step-back method such as is used for louvre sections of air-conditioning cabinets, thus simplifying mold construction (see Fig. 11.25).

Direction of movement of mold plate

Direction of movement of mold plate

Cross section of mold

Open slots

Molded part
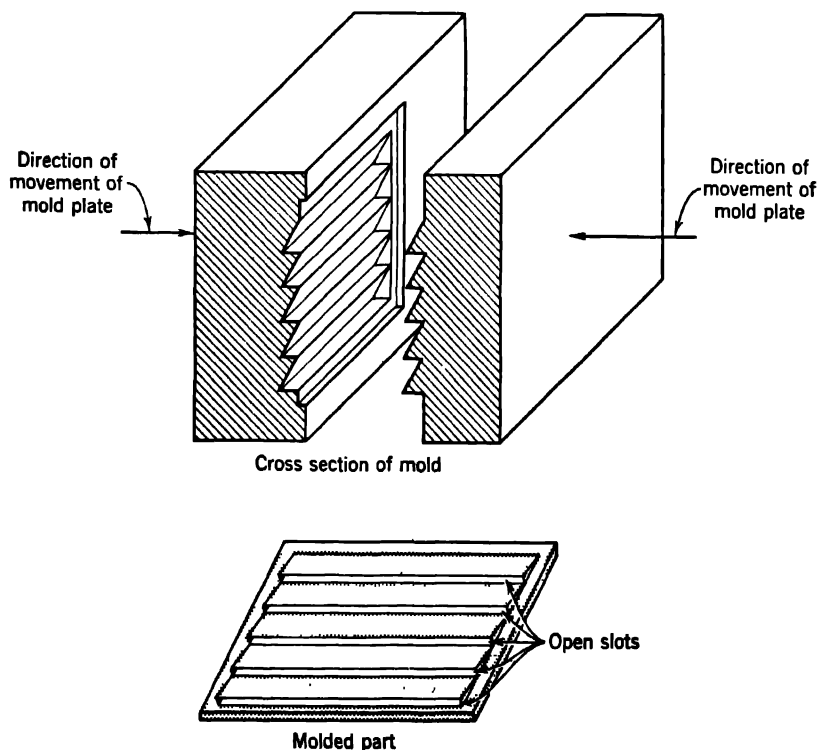
FIG. 11.25. Step-back mold for producing side holes in louvred section.

| Undercut required | Section *A–A* | No undercut required | Section *A–A* |

(*a*)   (*b*)
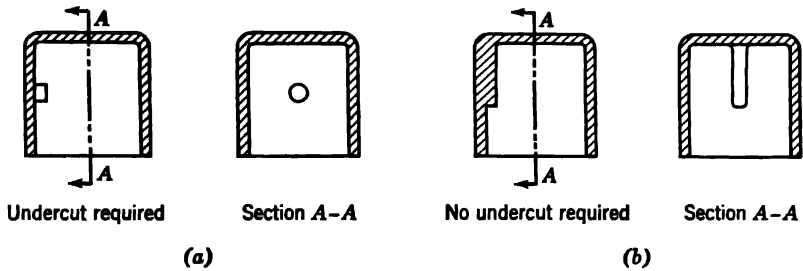
FIG. 11.26. Method of avoiding undercut for a side boss.

Overhanging bosses or undercuts can sometimes be molded without loose pieces in the mold by adding material or dividing the part into two pieces (see Fig. 11.26).

11.40 THREADED PARTS

Threads may be molded or tapped in almost all plastic materials. The American National form of thread is preferable. Other threads, such as a rolled thread for fuses and lighting fixtures and round profile threads for closures and bottle tops, can be molded readily but not tapped.

In general, threads above ¼ in. diam should be molded and smaller threads machine tapped. Use tapped metal inserts if maximum strength or frequent use is required. Do not mold threads smaller than size No. 8 or finer than 36 threads per in.; fine and shallow threads tend to fill with pure resin and are brittle. Molded threads are stronger and will hold their dimensions better than tapped threads, which tend to swell where the resin has been cut. Do not retap a molded thread.

Molded threads should begin and end abruptly (see Fig. 11.23). A hole extending below a molded thread should be smaller than the root diameter of the thread so the mold pin can be removed. Tapering of this portion of the pin facilitates its removal. If the pin forming the thread is stationary in the mold, provision must be made to unscrew the molded part. External threads produced by split molds eventually need chasing of the thread at the parting line and provision should be made for this in determining production tooling costs.

Threads can be tapped as fine as 56 threads per in. Do not tap threads over ¼ in. in diam. Mineral-filled compounds are brittle and are difficult to tap without chipping. Fabric-filled materials

tap readily but the exposed cut surface will tend to swell when moisture is absorbed. Tapped threads can be held to a Class II fit (A.S.A.) on low moisture-absorbing materials on diameters under ¼ in. When molded or drilled holes are to be tapped, allow an adequate cross section, make the hole relatively shallow (taps will clog on long holes), or tap through the hole if possible.

11.41 INSERTS

Inserts mean extra molding costs and should be avoided whenever possible. Inserts for parts that are to be compression molded, especially if using rag-filled material, should be of brass or steel and sturdily designed to withstand molding pressure. The portion of the insert that is anchored in the compound should be no longer than twice its diameter for an insert supported at one end only; no more than 4 times its diameter for one supported at both ends. If the part is to be transfer molded, inserts such as brass strips, copper wires, or aluminum rods of almost any dimension can be successfully molded.

Adequate anchorage must be provided for inserts molded into a part. A medium or coarse diamond knurl is practically always sufficient. But if the insert is to be subjected to great axial strain, grooves cut around the circumference of the insert will help. The slot in an embedded screwhead does not provide good anchorage against turning.

Specify whether the insert shoulder is to be below, above, or flush with the compound. If the insert is to be used as a mounting boss or electrical terminal, it should be above the level of the molded part (see Fig. 11.27). In this way the insert itself must absorb all the axial tensile strain, and none of it will tend to pull the insert from the compound. If the insert is to hold a mating part snugly to the molded part, or is to be used for assemblies, the shoulder of the insert should be flush with the surface (see Fig. 11.28). This will allow the mating part to be drawn down firmly, but will not tend to pull the insert out. An insert that projects above the molded part requires a corresponding depression in the mold. Irregular depressions are difficult to make; therefore, design inserts with round projecting portions, if possible.

An adequate wall thickness must be allowed to cover the anchorage of the inserts: for ¼ in. diameter inserts, a ³⁄₃₂-in. wall is minimum; for ½-in. diam, a ⅛-in. wall is minimum; for over ½-in. diam inserts, do not use less than ¼-in. wall.
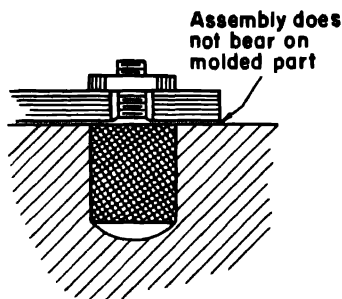
Fig. 11 27. Insert for electrical
terminals.
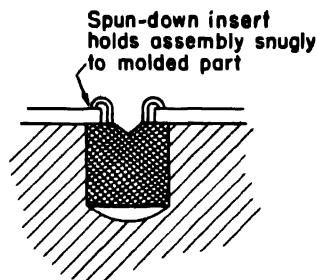
Fig. 11 28. Insert for assem-
bling a mating part snugly to
a molded part.

Tolerance on the minor diameter of commercial female inserts
may be as great as ±0.006 in. Since these inserts may shift on
their supporting pins, the permitted centerline tolerances must be
large if they are specified. It is better practice to use inserts held
to close tolerances, such as ±0.001 in. or ±0.002 in., whenever the
insert must fit the mold.
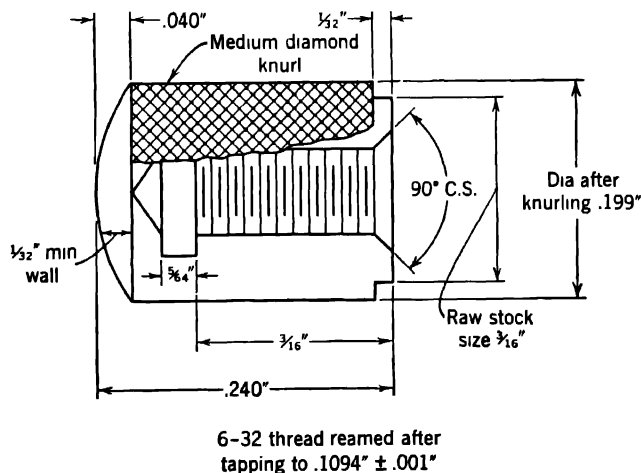
Fig. 11.29. A typical standard female insert.

A typical standard female insert is shown in Fig. 11.29. Note
that the knurl is terminated $\frac{1}{32}$ in. from the face, that the end
is curved, that the threads are undercut to provide full threaded
depth, and that the thread is slightly countersunk These are all
good features.

In designs for electrical apparatus, sharp corners and points on inserts raise voltage gradient and lower dielectric strength in the compound. If electric arcs between inserts are probable, provide a fiber or rubber insert or an air gap to prevent the arc from traveling on and carbonizing the plastic surface.

11.42 DIMENSIONS, TOLERANCES, AND SHRINKAGE

Tolerances are the margins allowed for unintentional variations that occur during manufacture. They are necessary on molded parts because of the unintentional variations in molds, molding technique, compound, and finishing.

The tolerances obtained commercially on fixed mold dimensions for hot-molded phenolic parts are:

Nominal Dimension, in.	Preferable Tolerance, in., min	Close Tolerance, in., min
½	±0.005	±0.002
1	±0.008	±0.003
2	±0.012	±0.005
4	±0.016	±0.010
6	±0.020	±0.015

Do not require close tolerances unless absolutely necessary; close tolerances require very costly tool construction and cause a high percentage of rejects.

Cold-molded parts will require about twice the preferable tolerance for hot-molded pieces. Parts of urea require approximately the same tolerances as those shown for phenolic parts, but allowance must also be made for after-shrinkage of 6 to 8 mils per in. which takes place within a year.

Dimensions across the parting line in compression molding must include an additional allowance for build-up of material. Allow ±0.010 in. for wood-flour-filled compounds, ±0.015 in. for large wood-flour-filled parts, small rag-filled parts, or parts from multiple-cavity molds; and ±0.025 in. for large rag-filled parts. Transfer molded parts can be made with only a ±0.005 in. allowance, if necessary.

At least ±0.003 in. should be allowed for warpage per linear in. of a flat surface, as measured by the sagitta of the arc.

Molded parts should not be used for the precision parts of sensitive instruments because all plastics show some after-shrinkage

upon aging. The ureas and some thermoplastics are worse in this respect than the phenolics. Their after-shrinkage is increased by hot, dry service conditions. After-shrinkage and thermal expansion may also cause plastic parts to crack if they are rigidly fastened to dissimilar plastics or to a metal frame.

11.43 APPEARANCE

The best surface finish requires a highly polished, expensively finished mold; a fine filler and high-resin-content compound; provision to hide flow marks, rib and boss shadows, and knockout marks; and careful handling, wrapping, and special packing. Buffing produces a more highly polished surface, but will not wear as well as a nonbuffed surface.

Large flat areas should be ribbed, stippled, or broken into designs to hide flow marks. Knurled areas are decorative and provide a good grip. Sudden thickness changes, ribs, bosses, and inserts show through on translucent or transparent parts, and are usually very unsightly. Provision may be made to hide them with a surface rib, knurl, or other design.

Molded parts usually carry the molder's trademark, cavity numbers, and knockout pin marks. Surfaces on which to locate these should be shown on drawings.

11.44 AIDS TO FINISHING

Parts can frequently be designed to facilitate the cleaning of the flash which generally occurs at the parting lines on thermosetting parts, or the removal of gating marks or other finishing operations. Parting lines should fall on square edges or on crowned or ribbed surfaces which are readily accessible for filing. Flash forming around wedges, knockout pins, and plugs or name plates should be easy to clean.

Particular attention should be given to parting lines on decorative handles or knobs because such flash must be removed evenly, without marring the surface.

Inserts and electrical contacts that must be faced should project slightly above the compound.

11.45 COATING AND DECORATING

Numerous paints that have excellent adhesion and do not cause surface cracking are available for application to plastics. Paints have done much to overcome the appearance drawbacks in the dark

colored parts, such as the phenolics, and permit multicolored combinations to be used on the more brightly colorable plastics. With transparent parts painting is often done on the reverse side, so that the plastic provides a lustrous, attractive fronting that protects and highlights the painted areas.

Metallic coatings may be applied to plastics either by electroplating or vacuum metallizing. In electroplating, the plastic may be made electrically conductive either by incorporating conductive materials with the resin or by sandblasting the surface and chemically depositing a thin layer of silver on the surface. Vacuum metallizing is generally used for decorative purposes only and it consists of applying a thin layer of clear lacquer on the surface of the plastic which fills up the microscopic pits and provides a better bonding surface for the vaporized aluminum which is subsequently deposited as a thin (1 millionth of an in.) layer under vacuum conditions.

Designs or intricate lettering can be applied to a part by photoengraving or etching the mold. This produces a quite legible reproduction raised about 0.003 in. For higher letters the mold is engraved. A common value is 0.010 in.; letters above 0.030 in. should include taper and a fillet at the base.

Sharp metal stamps will print or roll onto a surface without heat. Deep relief branding of thermoplastic or thermosetting plastics is done with a heated die, and letters are 0.006 to 0.008 in. deep.

Letters to be filled with paint should have sharp edges, be 0.005 to 0.030 in. in width, half as deep as they are wide, and have bottom corners rounded. These letters are fairly expensive because they must be raised on the mold which requires undercutting the entire mold surface.

11.46   CONCLUSION

The development of many of the plastic materials described in this chapter has occurred since 1935. The unique properties possessed by some of them have brought forth the concurrent development of new processes such as blow molding and low-pressure laminating. In turn, some of these process developments, undertaken to exploit properties of new materials, have resulted in new uses for the older materials.

The rapidity with which the plastics art has grown is indicative of the continuing improvements that can be expected in the future. The engineer should therefore recognize that an impractical or im-

possible design today might tomorrow be readily produced by some improved material or method. Meanwhile, the existing array of plastic materials and processes described provides a broad and versatile field, which should challenge the imagination of the design engineer.

Review Questions

1. What characteristic is common to those plastics classed as thermoplastic? How do they differ from thermosetting plastics?

2. Name the various components which may make up a molding compound, and tell the function of each.

3. What characteristic properties do the following fillers impart to a molding compound: wood flour, rag fibers, asbestos, mica, macerated cloth, and carbon?

4. Name six of the more widely used thermoplastic resins and indicate a typical product and the resin property especially required for that product.

5. What thermosetting resin is most used of this type of plastics? Name a typical product made with this resin and indicate the resin properties required for it.

6. Name four thermosetting resins, in addition to that in question five, and indicate typical products and resin properties for each.

7. What is the main advantage of injection molding for thermoplastic parts as compared with hot-compression molding?

8. In what two types of molding is the injection process applied to thermosetting resins? Describe one of them.

9. What is the difference between hot-compression molding and transfer molding? For what type of work is the latter used?

10. For what type of parts is extrusion usually used? laminating? Explain the low-pressure method of laminating. How does high-pressure laminating differ from the low-pressure process?

11. Describe the blow-molding process, the class of resins used, and name a typical product.

12. In what two ways does cold molding differ from hot-compression molding? What kind of parts are made by cold molding?

13. What is the principal advantage of the casting method of molding plastic parts? What two design requirements are particularly important for molding parts by this method?

14. Compare the following processes with respect to (a) the production of sheets, rods, and tubes; (b) production of intricate shapes; (c) choice of materials permissible; (d) strength of parts which can be produced; (e) dimensional accuracy; (f) tool cost; and (g) production rate: hot-compression molding, hot-injection molding, extrusion, laminating, casting.

15. (a) Name two factors that influence the accuracy to which plastic parts can be molded. (b) What are good working tolerances for hot-molded phenolics (1) on dimensions parallel to the line of molding pressure and (2) on dimensions perpendicular to the line of molding pressure?

16. The following suggestions are considered to be good practice in the design of molded plastic parts under most circumstances. State briefly the reasons which support each.

(a) Sharp corners should be avoided unless produced in a mold built up of sections, or unless located at the parting line.

(b) Walls.should be as uniform as possible.

(c) The minimum wall thickness in phenolics is 0.025 in. and the maximum on large pieces is 1 in.

(d) Generous radii should be used to join changes in section.

(e) Inserts for compression molded parts should be flush or raised from the surface if they are used for fastenings.

(f) The slenderness of $\frac{1}{16}$-in. diameter cantilever pins should not exceed 1:1. Larger pins may be 2:1.

(g) Threads greater than $\frac{1}{4}$ in. in diameter should be molded and smaller threads machine tapped.

12 RUBBER

by A. M. VARNER *

The outstanding property of rubber, which is of primary interest to the design engineer, is its tremendous energy-storing capacity. Its quality of storing energy is evidenced in the unusually high elongation and the almost instantaneous return to its original dimensions upon release of applied loads.

The characteristic of "rubberiness" was known for many centuries, but the application of rubber began with the discovery of vulcanization by Charles Goodyear in 1839. He added sulfur and basic lead carbonate to natural rubber and heated the mixture, and thus changed the material from a plaything or, at best, an unsatisfactory weatherproofing material to the useful product that we know today. Since 1839 much has been learned of the basic chemistry of rubber and a great deal has been done to improve the methods of vulcanization, to increase its tensile strength, tear resistance, heat resistance and aging resistance, and to utilize it in a myriad of products ranging from the highly flexible latexes to bone-hard "ebonites."

12.1 CLASSIFICATION

Three major classes of materials which exhibit the characteristics of rubber are: (1) natural rubber, (2) synthetic, or American-made, rubber, and (3) rubberlike plastics. Natural rubber is of botanical origin and it may be found in the juice of many plants, such as the shrub guayule, or in goldenrod, Russian dandelion, milkweed, and many other shrubs, vines, and trees. However, the principal and virtually only source is from the *Hevea brasiliensis* tree, which produces the best rubber latex. Although much is known of the chemical characteristics of rubber, its chemical structure has not yet been fully duplicated in the laboratory. Numerous attempts to duplicate natural

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rubber have led to the development of a group of highly useful products known as the synthetic, or American-made, rubbers. Such materials as Buna N or S, Neoprene, Perbunan, Thiokol, Polyisobutylene, Hycar, and Butyl come under this category. The third group, the rubberlike plastics, or plastic *elastomers,* are materials which exhibit the characteristics of rubber, but are of a basic chemical structure that is decidedly different from that of natural rubber. Silicone rubber, plasticized polyvinyls, polyethylene, flexible polyesters, ethyl cellulose, and rubber phenolics are in this category.

12.2 COMPONENTS

Crude natural rubber, by itself, is not a very useful material. However, by the proper selection and mixing with other materials, the crude rubber may be compounded into products that are outstanding in tensile strength, tear, abrasion, chemical or heat resistance, adhesiveness, hardness, or any of a number of other desired properties or combinations thereof. The materials that perform the transformation of the crude rubber are classified under the categories of vulcanates, accelerators, antioxidants or age resistors, fillers, reinforcing agents, and colorants. Some components in a rubber compound overlap in the role that they play and thus fall into several categories.

12.3 VULCANATES

Simply stated, the vulcanate reduces the plasticity of the rubber compound, while maintaining its elasticity. Sulfur was the original material and is still the chief material used for this purpose. The basic function of vulcanization can be performed by other materials, such as sulfur chloride, nitro compounds, selenium, or halogenated quinones. Each of these imparts slightly different properties to the compound and are used whenever the rubber technologist finds them most advantageous to a specific application. Vulcanization will generally result in a marked increase in tensile strength, a reduction in tendency to lose flexibility at low temperature, and an increase in the resistance of the rubber to solvents.

12.4 ACCELERATORS AND ACTIVATORS

As with many chemical reactions, the use of an accelerator results in a reduction in the amount of time necessary for the vulcanization reaction to reach completion at a given temperature. Accelerators for rubber also produce additional advantages, which make them indispensable to rubber manufacturing. Some of these advantages are:

(1) a reduction in the quantity of sulfur required and a consequent elimination of "blooming" of excess sulfur to the surface of the finished article; (2) a leveling effect on the degree of vulcanization, which lessens the possibility of overcure and permits thicker articles to be evenly vulcanized; (3) a leveling effect on the variation of vulcanization of various crude rubbers, which permits greater latitude in the selection of crudes for compounding; (4) counteraction of the effect of carbon black to prolong the time of vulcanization, which occasionally would be of such duration as to prohibit the use of carbon black in some articles; (5) improvement in resistance to deterioration to the final product; and (6) utilization of brighter and less expensive organic colorants, which would be impaired by prolonged vulcanization time. Organic materials such as guanidine, aldehydeamine, and carbon disulfide derivatives and thiazoles are most commonly used as accelerators.

Some materials have the property of facilitating the function of accelerators and are called activators. Zinc oxide is such a material and it is almost universally used in compounds for this purpose.

12.5 ANTIOXIDANTS OR AGE-RESISTORS

One of the major problems of rubber is that over a prolonged period of time under normal room-temperature conditions vulcanized natural rubber will show a decided decrease in tensile strength. If its service conditions include flexing operations, cracks will appear on the surface of the rubber and it will begin to deteriorate. Heat, light, elongation, presence of copper or manganese salts or soaps, and improper vulcanization by incorrect time or temperature are some of the various factors which accelerate this deterioration. But its principal cause is oxygen. Therefore, materials that inhibit the reaction of oxygen with the rubber, such as many of the previously mentioned accelerators, phenols, amines and waxes,* are incorporated into the compound to serve as antioxidants or age-resistors. Although not all antioxidants have proved to be effective as age-resistors, it is almost invariably true that any good age-resistor is also a powerful antioxidant.

* Waxes are solely used for protection against deterioration by light and ozone. Wax-antioxidant combinations furnish the best protection against chalking and sun checking.

12.6 FILLERS, REINFORCING AGENTS, AND COLORANTS

It is somewhat difficult to form a sharp distinction among these three terms since some substances, such as zinc oxide and carbon black, serve several purposes at the same time. Broadly speaking, a material is a reinforcing agent when the tensile strength is increased by its incorporation into the compound. On this basis, carbon black is outstanding, for it increases tensile strength to a considerable degree over a wide range of loading. Magnesium carbonate, zinc oxide, and China clay also increase tensile strength, but to a lesser degree in the order named. Talc and similar materials show little increase in tensile strength and function almost exclusively as filler materials Colorants are usually organic materials, and generally only minute quantities are needed. Other materials such as oil, resins, asphalts, waxes, and tars are often added to facilitate mixing and to impart permanent softening or plasticizing action to the compound.

Rubber Materials

12.7 NATURAL RUBBER

As the rubber is withdrawn from the tree, it is in the form of a latex, which is a suspension of rubber globules in a watery serum The latex has a natural tendency to coagulate on contact with air, and this tendency is usually accelerated by the addition of formic acid. If the rubber is to be processed into crepe form, the coagulum is washed on a series of mills, the rolls of which operate at different speeds causing a partial breakup of the rubber globules. Some of the rolls are fluted to permit easier removal of the serum, and this gives the crepe appearance to the rubber stock. If the rubber is to be processed to smoked sheet, the coagulum is merely passed through press rolls to squeeze out the major portion of the water and serum, and then the sheets are hung in smoke houses to cause further drying. The smoke particles also have an inhibiting action on the remaining serum which prevents bacteriological mold growth. Both the crepe and the smoked sheet processing operations are performed at the plantation site to reduce the weight of the crude rubber for shipping to the manufacturer. Starting with these crude rubbers, the manufacturer adds the necessary components, which were discussed above, and performs appropriate mixing, milling, filtering and calendering, or extruding, molding, or fabricating operations to produce the desired marketable item.

If it is desired to utilize the latex from the tree as a latex, ammonia is added to prevent natural coagulation from occurring. The latex is then concentrated by various methods, such as creaming, centrifuging, electrodeposition, and evaporation, to remove as much excess water as possible and still maintain a product of fluid consistency. The production of latex products is accomplished by coagulation of the latex after it is in the desired shape or form. Care must be exercised, particularly during compounding, to prevent premature coagulation. Rubber in the form of latex is used for operations involving dipping, casting, foamed products (sponges, etc.), impregnating and coating, making of rubber thread, and other techniques and applications which would be impracticable with solid rubber sheets.

Some of the properties which can be found in natural rubber products are high energy-storing ability, elongation range of 1 to 1000 per cent, noncompressibility, resistance to most inorganic acids, alkalics, and salts and to many organic solvents. Swelling occurs in a number of solvents such as gasoline, naphtha, turpentine, and carbon tetrachloride. Density averages 23–25 cu in. per lb, electrical-resistance values range to 550 volts per mil, and heat resistance is as high as 375 F, with an average around 150 F. Slow oxidation occurs in air and is accelerated by heat and light.

12.8 SYNTHETIC, OR AMERICAN-MADE, RUBBER

Petroleum and coal products form the basis for most synthetic rubber. Since the products from these two sources can be obtained in a relatively high degree of purity, it is possible to produce a more consistent product than can be produced from natural rubber. In addition, the synthetics possess properties such as oil resistance, aging resistance, and low temperature flexibility which are far superior to natural rubber. Over half the mechanical rubber goods presently produced are of synthetic rubber, and their advantageous properties have made possible applications not previously possible with natural rubber. However, natural rubber has the advantages of low cost and better energy-storing capacity and should continue to play a significant role for some time to come.

Some of the more prominent synthetics, their basic composition, and their main advantages or disadvantages are as follows:

GR-S. This material, a copolymer of butadiene and styrene, shows handling characteristics and properties that are more nearly like those of natural rubber than any of the other synthetics. It is not oil re-

sistant, but it shows aging-, heat-, and abrasion-resistant properties that are superior to those of natural rubber.

Nitril (Buna N). A copolymer of butadiene and acrylonitrile, this material shows excellent resistance to abrasion and aging as well as good resistance to oil and solvents. The low temperature flexibility of this material is poor compared to natural rubber. Incorporation of this material into phenolic molding resins results in the versatile rubber-phenolics. These rubber-phenolics have greater vibration, fatigue, impact, and thermal shock resistance than is possible with the phenolic alone.

Neoprene. This material is a polymer of chlorobutadiene, which depends on polymerization rather than vulcanization to achieve its optimum properties. Neoprene shows excellent resistance to ozone and a combination of good resistance to oils, sunlight, heat (300 F continuous), and aging as well as good mechanical properties.

Butyl. Butyl rubber is a copolymer of isobutylene and isoprene or butadiene showing good resistance to vegetable oils, lards, and oleic acid. It has excellent resistance to strong acids such as nitric, sulfuric, hydrofluoric, etc., but otherwise has generally poor resistance to chemicals. Its high impermeability to gases, coupled with excellent heat, tear, and abrasion resistance make it a superior material for inner tubes.

Polysulfides (Thiokols). These are copolymers of sodium polysulfide and ethylene dichloride or dichloro-ethyl ether. They are resistant to a wide range of solvents, some grades swelling only slightly in such active solvents as acetone and carbon tetrachloride. Resistance to ozone, sunlight, and aging is excellent. Disadvantages of these materials are physical properties that are generally inferior to other synthetics and a highly undesirable onionlike odor.

Polyisobutylene (Vistanex). This material is a polymer of isobutylene which can be produced in a wide range of molecular weights from soft sticky gums to tough elastic solids. The products are nontoxic, tasteless, and odorless, and have excellent resistance to acids and alkalies. Most of the applications of polyisobutylene involve incorporation with other materials or other synthetic rubbers to enhance their properties. The high-molecular-weight polymers have been used very successfully as linings for corrosive chemical tanks.

12.9 RUBBERLIKE PLASTICS OR ELASTOMERS

Several materials exist that differ considerably in basic chemical structure from rubber but exhibit properties of considerable flexibility,

resilience, and, to a limited degree, elasticity. Silicone rubber, polyethylene, flexible polyesters, and certain grades of polyvinyl butyral, polyvinyl alcohol, and polyvinyl chlorides show such properties.

Silicone rubbers possess unusually low temperature flexibility, remaining flexible as low as −100 F and yet have continuous heat resistance as high as 350 F. Their resistance to water and petroleum oils is high but they tend to swell in aromatic solvents. Silicones are not compatible with the natural or synthetic rubbers.

Polyethylenes (see also Chapter 11), because of their chemical and water resistance and wide flexibility range, are finding many applications in wire insulation and chemical equipment formerly using rubber.

Polyesters (see also Chapter 11) can be vulcanized with sulfur to give products that are flexible at low temperature and resist gasoline and oils.

Three of the polyvinyls have found considerable application. Polyvinyl butyral has been used for a considerable time as the inner layer of shatter-proof glass. Polyvinyl alcohols show outstanding imperviousness to all water-insoluble solvents and gases. Plasticized polyvinyl chlorides are resistant to solvents, oils, abrasion, sunlight, chemicals, and flexure. All these materials are replacing rubber to an increasingly large extent and are opening up new fields for flexible materials.

Rubber Processing

12.10 PROCESSING

Rubber arriving from the plantation sites is graded according to the methods of treatment and source of materials. The various grades are: (1) ribbed smoked sheet; (2) pale crepe (thick or thin); (3) latex; (4) guayule; (5) fine Pará; (6) blanket; (7) browns; and (8) flat-bark crepe.

Each of these grades finds a specific use in industrial applications. The ribbed, smoked sheets are most generally used for tire treads and carcasses, footwear, and cable insulation. Pale crepe is cleaner than the other types and is used for translucent or light-colored goods. Latex is used for impregnating, dipping, or sponge applications. Guayule has a high resin content, is very soft, and is used to give other rubber materials tackiness. Fine Pará is used for high-grade spread (sheeting) goods, rubber thread, wire and cable insulation, and cements. Blanket rubber has a definite color and odor, and contains

Table 12.1 Some Comparative Properties of Rubber and Elastomers

	Specific Gravity	Tensile Strength, psi (max)	Elongation at Break, % (max)	Durometer "A" Hardness	Maximum Service Temperature, °F	Abrasion Resistance	Effect of Sunlight	Resistance to Aging	Resistance to Petroleum Solvent
Natural rubber, hard	1.18	11,000	5	70–100	220	Good	Discolors	Excellent	Fair
Natural rubber, soft	1.15	6,000	650	30–80	180	Excellent	Deteriorates	Good	Poor
Buna S	0.93	3,000	650	30–90	300	Excellent	Slight	Good	Poor
Nitrile	0.96	4,000	600	40–90	300	Excellent	Slight	Very good	Excellent
Neoprene	1.35	4,500	760	25–95	300	Excellent	None	Very good	Excellent
Butyl	0.92	3,000	750	35–85	300	Good	None	Very good	Poor
Thiokol	1.35	2,000	650	40–100	250	Good	None	Excellent	Excellent
Polyisobutylene	0.91	1,500	600	..	.	Good	None	Very good	Soluble
Silicone	1.5	650	225	45–85	400 *	Fair	..	..	Poor
Polyethylene	0.92	1,800	550	45	106 †	Fair	..	..	Good
Polyvinylchloride, hard	1.4	9,000	2	80–100	212 †	Good	None	Excellent	Good
Polyvinylchloride, soft	1.3	2,000	350	40–80	190 †	Excellent	None	Excellent	Good
Polyvinylalcohol	1.26	5,000	..	..	250	Good	None	Excellent	..
Rubber phenolic	1.31	4,500	..	30 ‡	125 †	Good	None	Excellent	..

* 520 F for short time.
† Heat-distortion temperature—ASTM D648.
‡ Rockwell "M" scale.

foreign material. It is generally blended with smoked ribbed rubber. Browns are dark in color, variable in quality, and generally are blended with other grades. Flat-bark crepe is a low-grade material of a considerable foreign-material content and is used in low-cost articles.

12.11 MILLING OR PLASTICATION

The purpose of this operation is to overcome the elasticity, or "nerve," of the crude rubber to achieve a homogeneous plastic form into which the various desired components may be thoroughly mixed. The crude rubber is subjected to a compressive and tearing action by two rolls turning on each other at different speeds. For small batches (50–200 lb) this operation is performed on open-roll mills. For larger batches Banbury mixers are used.

Latex solutions are mixed in a different way. The compounds are usually added as water dispersions and mixing is done by mechanical stirring or on ball mill where the action of mixing will not generate heat which would result in premature coagulation.

12.12 VULCANIZING

The effect of vulcanization is to change from the plastic state brought about by milling to a state of ultimate strength and elasticity. The action is usually brought about by steam heat of the order of 250 F over a 5- to 50-min time period.

Since no heat is generated in the mixing of latex which would cause prevulcanization, ultra-active accelerators can be incorporated and low temperatures employed for vulcanization. This system makes possible the use of low-cost open molds to produce nonsagging, tack-free products such as rubber footwear, bathing caps, and seamless gloves.

In the formation of manufactured goods, vulcanization is performed after extrusion, calendering, and latex forming. In molding operations, vulcanization is simultaneous with molding. Lathe cutting and other fabricating operations must be performed after vulcanization.

12.13 EXTRUDING

Pieces of constant cross section are usually extruded. Extruded rubber products generally have a durometer hardness greater than 45 because of the difficulty of maintaining dimensions on softer materials. Extrusion dies are inexpensive, and one of the more familiar

applications is the extrusion of insulation on wire. The extruded product may be coiled or cut up into strips to be later vulcanized in open steam heaters.

12.14 CALENDERING

In the production of sheets of definite thickness or coating rubber on fabrics, a group of three or more large steel rolls are used. These rolls are arranged one above the other and the desired results are achieved by the speed and direction of rotation of the individual rolls. For rubber sheets three rolls are used with the top and bottom rolls turning in one direction and the middle roll in the opposite direction, all rolls operating at the same speed. Thicknesses as low as 0.003 in. are obtained by this method. For coating fabric, the same set of rolls may be used, with the cloth passing between the middle and bottom rolls along with the rubber sheet. For squeezing rubber into the fabric, or "frictioning," the middle roll is run at greater speed than the top and bottom rolls, thus grinding the rubber into the fabric and surrounding each fiber with rubber.

12.15 MOLDING

Molding is performed in heated, matched metal molds under high pressure to insure a nonporous uniform product of good dimensional tolerances. Precutting of unvulcanized sheet stock to a rough approximation of the finished piece is often necessary because of the poor flow characteristics of the rubber. Since rubber is noncompressible, the charge to the mold is usually weighed. Provision is made for overflow of excess material which can be removed after molding by die cutting, abrasion wheel grinding, or tumbling. Since parts are vulcanized during molding, the cycles of operation are slow, running between 5 and 50 min per cycle.

12.16 SPONGE OR FOAM RUBBER

These materials are formed by the inclusion of chemicals in rubber compounding which form gases during vulcanization. Sodium bicarbonate is a commonly employed rising agent for sponge materials. Nitrogen-releasing compounds are used to produce a nonconnecting unicellular structure which does not absorb moisture and finds use in floatation equipment. Sponge-rubber products may be obtained with a solid rubber cover molded on the exterior. Grades of rubber sponge are designated as soft, medium, and firm.

Sponge-rubber products made from latex are produced by beating air into the latex to make a foam and then vulcanizing the foamed mass. Latex sponges are extremely soft, are stronger than ordinary sponge, and have longer service life. Latex sponges find application in cushioning for a wide variety of upholstering.

12.17 DIP MOLDING

In molding products from latex, two general methods are used. One is to coat the mold form (usually aluminum) with a layer of coagulant and then to dip the mold form into the latex solution, where a coagulated layer will form on the mold. The mold form is then withdrawn from the latex solution and heated to bring about vulcanization of the layer. The second method is electrodeposition. It operates on the same coagulation principle, except that the coagulation action is caused by the release of cations at an anode in a latex solution. Neutralization of the charge on the individual globules causes them to coagulate around the anode, which is in the form of the article being molded. Both these methods find use in the production of hollow, seamless articles such as balloons and rubber gloves.

12.18 LATHE CUTTING AND DIE CUTTING

It is sometimes more economical to produce parts like washers, discs, or cylinders by extruding a rod or tube, vulcanizing it, and cutting the desired lengths on a lathe. Along these same lines, calendered sheets may be vulcanized and the desired parts stamped out by dies such as would be done with sheet-metal parts.

Applications

12.19 APPLICATIONS FOR RUBBER

Pneumatic tires and tubes gave the rubber industry its greatest impetus and are still the leading applications for rubber products. An evergrowing application is for use as belting material in the V-belts for power transmission and for the various conveyor belts in transporting a variety of goods such as grain, sand, coal, ice, ore, slag, and packaged goods. V-belts are quiet, compact, nonslipping, shock absorbing, clean, and have long life and low cost. V-belts and conveyor belts are constructed with textile-cord cores (or, for high strength, flexible steel wires or cables are added) which carry the load with a covering of rubber to cushion against shock, to form a

barrier to moisture, and to eliminate friction between the fibers and the frictional contact with pulleys.

Gaskets. Another large and important applicaton for rubber products is for gasketings suited to many types of construction and for sealing any of a variety of materials. Typical types are extruded hollow shapes for refrigerator-cabinet door seals, square slit strip for flange seals on watertight cases, flat sheet die-cut forms for screwed connectors, and tubular forms for couplings.

Mountings. Most mountings are sections of rubber sandwiched between two metal plates. Their principal purpose is to reduce or isolate machine vibrations, and, in turn, to prolong the life or to improve the quietness of the equipment. Another use is the protection of delicate instruments from external vibrations. A factor that is often overlooked when rubber mountings are used on machines is the increase in work efficiency because of reduced worker fatigue.

Hose. Most hose consists of an extruded tubular rubber core around which fabric or metal is wrapped or braided to provide resistance to pressure. An outer rubber cover is provided for mechanical protection. Hose is generally of one of two types: mandrel cured or long-length cured. Mandrel curing produces a smooth, uniform diameter interior, and this type of hose can resist higher pressures because of a more uniform construction of the reinforcing braid or wrappings. Lengths of mandrel cured hose are usually less than 50 ft. Long-length cured-hose lengths range up to 500 ft, offering the advantages of reduction of couplings, lower cost, and a smooth external surface. They are usually only 2 in. O.D. or less and are not generally used for pressures exceeding 800 psi. The design and type of rubber used in the construction of a hose varies with its intended use, and standard designs are available for applications involving steam, beverages, chemicals, sand, creamery products, fire hose, gasoline, underwater hose, hydraulic equipment, oxyacetylene hose, paint, and suction hosing.

Miscellaneous. Rubber lining materials are used in a variety of tanks for transporting and storing chemicals, for fume stacks, and containers for food products.

In the printing industry rubber has proved a versatile platen material which permits faster press operation with longer press life, easier installation, and a saving in ink.

Sponge rubber is used for vibration and shock absorption, water or sound absorption, thermal insulation, and for sealing against air, moisture, sound, and dirt, e.g., in automobile doors.

Rubber thread utilizes the highest type of pure gum rubber and

may be formed by cutting sheets or extruding from latex. Applications are shock-absorber cord, head bands for goggles and helmets, articles of clothing, bandages, and golf balls.

12.20 CONCLUSION

The many types of basic rubbers and elastomers, the potentialities of compounding and mixing them, and the variety of forming processes available make it possible to produce a custom-made rubber part to meet nearly any requirement. In this chapter, the broad nature of these possibilities has been briefly covered. Little emphasis was placed upon actual compositions or specific property values since these vary greatly with end-use requirements and the individual suppliers.

The engineer who needs a flexible component for a piece of apparatus should look to this field. His specification should cover the requirements of the application and should be as broad as possible to allow the supplier's rubber technologist widest latitude in formulating a suitable compound.

Review Questions

1. What are the three major classes of rubber or rubberlike materials? Which are of synthetic origin and which have a structural resemblance?

2. To what group of materials may the term "elastomer" be applied?

3. Describe the purpose of the following additives used with crude rubber: vulcanates; accelerators; activators; antioxidants; fillers; reinforcing agents; and colorants.

4. Compare the general property range and the field of application of the three major classes of rubber or rubberlike material.

5. Name five processing methods for forming rubber products, and describe the state of the raw material used and the manner in which vulcanization is accomplished.

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13 CERAMICS

by C. H. COMMONS *

13.1 INTRODUCTION

Ceramic materials are one of the oldest of our engineering materials. Although this is a metal age, ceramic products are still important, for they account for about 6.7 per cent of the tonnage of our major engineering materials as compared to 10.4 per cent for steel.

Products classed as "ceramics" are made either chiefly or entirely from earthy materials (inorganic solids), which are heated to a high temperature during manufacture. The industry, therefore, includes such dissimilar products as dinnerware, electrical and chemical porcelain, structural brick and tile, refractories, glass, porcelain enamels, and abrasives. The raw materials, fabrication processes, product properties, and applications of each are briefly discussed in this chapter. For convenience, the presentation is grouped under the headings: whitewares, bricks, oxide ceramics, glass, porcelain enamels, and abrasives.

Whitewares

The term "whitewares" ("clayramics" is also used) generally includes the various types of pottery, china, tile, and porcelain. All are characterized as hard, durable, and strong, but nonductile. When manufactured by the proper procedures they form a wide variety of articles having useful properties and esthetic values.

13.2 RAW MATERIALS

There is no universal raw material for ceramic bodies for all applications. Some naturally occurring clays contain suitable constituents for use without adulteration for certain products. Usually, however, the ceramic manufacturer blends a mixture of raw materials to form

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his product. Clay, flint, and feldspar are the principal materials used. To these may be added oxides, coloring materials, and fluxes.

The materials used have a wide degree of purification. In some cases, such as clays for brick, stoneware, etc., there may be no purification of the raw material other than a selection of the deposit from which the clay is mined. Conversely, in certain grades of china clay an elaborate process of water washing, separation as to particle size, and removal of the majority of accessory minerals is required to produce suitable grades for high-quality ceramic articles. Many of the oxide materials used for ceramic applications undergo extensive processing before they are of sufficient purity and of suitable physical characteristics for specific ceramic applications.

13.3 CLAYS

Clays are formed by the weathering decomposition of rocks. If found in the same place as the original rock after the more soluble materials have been leached away, they are geologically classed as "residual" or "primary" clays. If deposited in another location as the result of wind or water transportation, they are called "secondary." Secondary clays are often deposited in beds of materials, some quite extensive. They are roughly stratified according to particle size, as the result of water transportation, since the finer grains are more easily held in suspension.

The clays used differ widely in their compositions. They are generally some combination of hydrated aluminum silicate, which may be of one or more crystalline forms, and of a considerable range of ratio of alumina (Al_2O_3) to silica (SiO_2).

The principal properties of clay are its plasticity and its bonding strength. All of them should have the property of becoming plastic when mixed with water. All have some bonding action on drying. The degree of plasticity and bonding action varies widely and is one method of classification. Clays are called "plastic," or "short," "strong," or "weak," depending on their relative values in these respects. Ultimate particle size is generally the principal cause of the variation. The finer the particle size, the stronger and more plastic the clay.

Another method of classifying clays is based on the color produced after firing. Brick, building units, and refractories in general are made of clays that burn to colors other than white. Sometimes the colors produced are of esthetic advantage. These colors are caused by impurities in the clays, usually oxides or compounds of iron, manganese,

vanadium, titanium, etc. Relatively small amounts of some of these elements produce considerable coloring effects. White-burning clays generally are more valuable for the production of whiteware such as dinnerware, porcelain, chemical ware, and tile.

A third method of classifying clays is based on the temperature at which the clay develops enough of a glassy bond to become vitrified * or nonporous. Pure clays having only small amounts of "fluxing" agents (oxides of alkalies, alkaline earths, or metals other than silicon or aluminum) are generally refractory. That is, they require high temperatures to develop enough glass to become soft. Presence of increasing amounts of these fluxing materials or larger proportions of silica lower the fusion point. Clays having enough fluxes to materially lower the vitrification temperature are called "soft," "low temperature," or "tight burning."

The term "kaolin" is used to denote an American white clay that is white burning. "China clay" designates the imported variety. These terms usually refer to a primary clay, although the secondary clays of Georgia and Florida are also known as kaolins. The kaolins generally have a higher fusion point, are coarser, and less plastic than "ball" clays. The latter are sedimentary clays that are dark in the unfired stage because of the presence of organic impurities. These burn out in firing, leaving a white color somewhat inferior to the kaolin type, principally because of iron and titanium impurities present. Ball clays are mixed with kaolin clays to improve plasticity and workability, and to improve the strength in green and fired states. The limit on additions of ball clay is its shrinkage, since plasticity and shrinkage increase together. Shrinkage is usually limited to 12 per cent for control of dimensions and warping. Bentonite (mainly $Al_2O_3 \cdot 4SiO_3 \cdot 9H_2O$) is also used to improve plasticity. It promotes this property more than any other similar material, but its addition is limited to 2 or 3 per cent for objects in which fired color is important because of the buff or red color it introduces. Shrinkage may be reduced by addition of nonplastic, and therefore nonshrinking, materials such as calcined (oxidized at high temperature) clay, ground flint, and other crushed or ground minerals.

13.4   FLINT

Flint is a common constituent of ceramic bodies. The name is no longer mineralogically correct but is a carry-over from the old prac-

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* Converted to glass.

tice of calcining (oxidizing) flint rock to shatter it and make the product more easily ground to proper fineness. More modern methods of crushing and milling, combined with location of purer ores, or ores which can be economically purified, have led to the general use of quartz (chemically pure silica, SiO_2) as the raw material. The ore occurs as sand, sandstone, quartzite, or occasionally as by-product quartz from mining. It is generally crushed to about sand size and then washed to eliminate the removable impurities. Some industries, such as the glass industry, use sand as such, but the whiteware industry requires a much finer-sized material. To obtain the required size reduction, the sand is fed into ball mills or similar equipment, where it is tumbled with larger balls (which may be flint, porcelain, etc.). The grinding action is accomplished by the force of the tumbling balls. The discharged material may be used as it is ground, or it may be put through various types of classifiers where the finer material is separated from the coarser and the latter returned for more milling.

Since flint is nonplastic, its addition lowers the workability and drying shrinkage of the body, and improves the drying behavior and strength. Properties imparted to the fired ware are strength, toughness, and hardness. A series of crystalline changes in silica at high temperatures are accompanied by relatively large volume changes which introduce strains in flint-bearing ceramic bodies, thus limiting their usefulness where very high temperature differences are encountered.

13.5 FELDSPARS

Feldspars are a class of alkali-alumina-silicate minerals that occur in igneous * rocks. They are generally not considered as commercial ores unless, because of geological formation, the rock contains a high percentage of the mineral in fairly large crystals or masses of crystals. *Microcline* and *orthoclase* are the common forms of the *potash feldspar* and have the composition corresponding to $K_2O \cdot Al_2O_3 \cdot 6SiO_2$. These are the minerals desired for high-grade porcelains such as electrical porcelain and the better grades of dinnerware. The corresponding *soda feldspar* is $Na_2O \cdot Al_2O_3 \cdot 6SiO_2$ and is called *albite*. Albite, and naturally occurring mixtures of albite and microcline, are used in a wide variety of bodies, glazes, and glasses. The *calcium feldspar* ($CaO \cdot Al_2O_3 \cdot 2SiO_2$) is seldom used in ceramic bodies as a direct constituent but is often present, since it forms an isomorphic (like-crys-

* Produced by "fire."

talline) series with albite in nature, and its separation is impractical. Several less common types of feldspars such as spodumene ($Li_2O \cdot Al_2O_3 \cdot 4SiO_2$), and beryl ($3BeO \cdot Al_2O_3 \cdot 6SiO_2$), are used for special applications.

In the unfired body the feldspars act as an antiplastic, reducing drying shrinkage and somewhat increasing strength. They may have some effect on workability. In firing the ware, the feldspar acts as a flux, becoming active first as the temperature is raised, dissolving the clay minerals and then the flint particles.

13.6 OTHER FLUXES

In addition to feldspars certain minerals of similar types are often used as fluxing ingredients. Nepheline ($Na_2O \cdot Al_2O_3 \cdot 2SiO_2$) occurring in igneous syenite dikes is becoming a very common body and glaze ingredient. Some lithium-bearing minerals such as lepidolite, amblygonite, and petalite are useful for certain applications.

Other fluxes are also used in ceramic bodies to lower the melting points. The list is too long to include each, but, in general, they may be classed as (1) natural, such as whiting ($CaCO_3$), barium carbonate ($BaCO_3$), and talc ($3MgO \cdot 4SiO_2 \cdot H_2O$); or (2) manufactured, such as soda ash (Na_2CO_3), zinc oxide (ZnO), and lead oxides of various compositions.

13.7 OXIDES

Except for SiO_2 (see "flint"), most of the oxides used in ceramics are manufactured from more complex ores of the compounds. Generally they are much more expensive than the mineral types of materials but are used for certain applications, as will be discussed in paragraph 13.25. Some of them, notably alumina (Al_2O_3), have become such large-scale production materials for other purposes that their prices have become fairly competitive.

13.8 MANUFACTURE OF WHITEWARES

The raw materials mentioned above are mixed in various proportions, depending on the properties desired in the finished product. Generally speaking, the compositions are chemically similar to those of the igneous rocks, and the fired products have hardness, weather resistance, and durability equivalent to these rocks. The whitewares are, however, more brittle because of a more glassy matrix.

The specific compositions used depend on the type and purity of materials available to the manufacturer, and on the product applica-

tion. Compositions used in the many branches of the industry will therefore be limited in this discussion to an illustrative example. The whiteware bodies used for technical purposes in electrical, chemical, or mechanical fields are known as *porcelains*. They may or may not be glazed, and are generally fired to a degree which approximates complete imperviousness. Many of the better qualities are known to retain very high vacuums for long periods of time. In a few cases the term is loosely used to include similar ware for low-voltage insulation made by dry-pressing (see below) methods which may not be impervious and may even have a measurable, although low, water adsorption. The mixture for porcelain products is usually composed of about the following range of raw materials:

	Per Cent
Ball clay	18–30
China clay	18–25
Flint	20–25
Feldspar	27–36

The materials are prepared for forming by two methods: the wet process and the dry process. Actual forming of articles prior to finishing, drying, glazing, and firing is accomplished by casting, extrusion, jiggering, throwing, and plunging with wet-process material, and by dry and vacuum pressing for dry process material (see Fig. 13.1).

13.9 WET PROCESS

In this process of manufacture the several clays, flint, and feldspars are mixed with water. A large excess of water is used so that the slurry or "slip" is sufficiently fluid to be screened to remove oversize impurities such as lignite, which occur naturally in the clays. The slip is then pumped into filter presses at about 100 psi, where the excess water is filtered out. The plastic cakes removed from the filter press are then ready for subsequent operations. If the material is to be cast, the purified plastic cakes are mixed with water in a *blunger* to form a casting slip. If the part is to be made by jiggering, throwing, plunging, or extrusion, the material is deaerated in a machine similar to a pug mill before forming.

A newer process is coming into use for extruding shapes, or for extruding blanks for jiggering and plunging. It employs mixing the raw materials in special types of powerful machines with just the right amount of water for the proper plasticity or workability. With this type of mixer it is necessary to use the purest grade of materials avail-
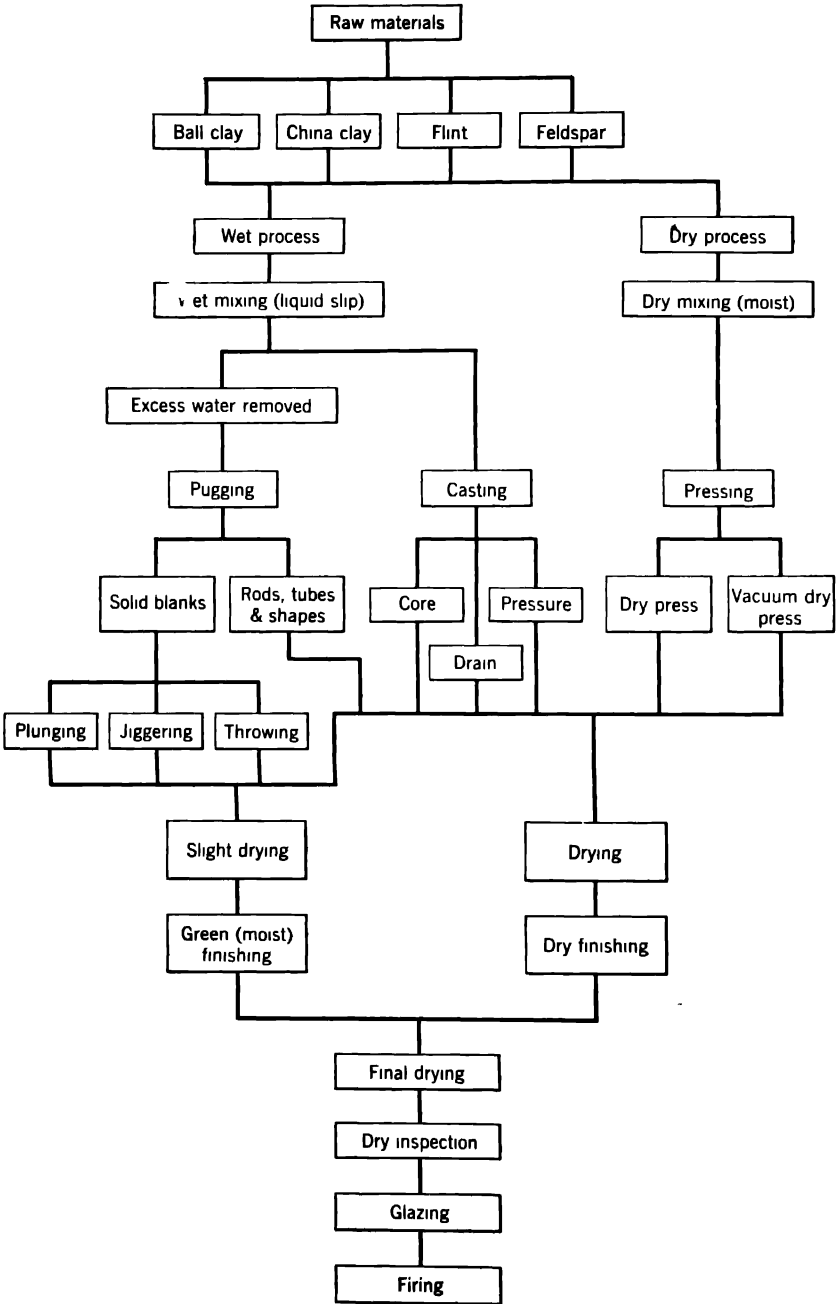
FIG. 13.1. Manufacturing processes commonly used in making porcelain.

able as the plastic mass is too stiff to allow screening out of foreign materials. The plastic material is generally put through a pug mill which does some further mixing but primarily works occluded air from the clay mass. It also compacts it into a coherent body, and extrudes the body through a nozzle to form the desired cross section (see Fig. 13.2). The nozzle can be a wide variety of shapes and can have
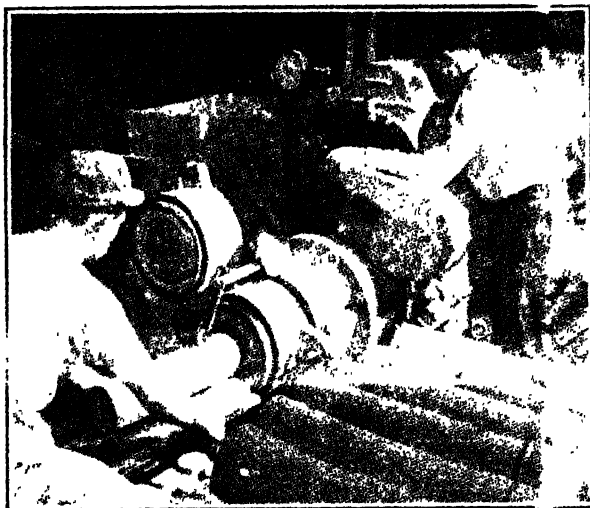
FIG. 13.2 Extrusion of green ceramic blanks from a pug mill.

one or more mandrels held in place so as to provide a hole or series of holes within the clay column as it is extruded. Shapes varying from rods, bars, and tubes to more complicated shapes for guy insulators can be extruded and the column cut to the desired lengths.

13.10 JIGGERING AND PLUNGING

If the desired shape is not economically formed from the extruded blank by a die without necessitating extensive trimming (such as shells, suspension insulators, etc.), a solid rod of the proper size is extruded and cut into the proper lengths. These "balls," "wads," or blanks are then put into a heavy mold made of plaster of Paris. The inside of the mold has the same shape as is desired for the outside of the insulator. The top or inner surface of the blank is formed by having a properly shaped tool forced down into the plastic material while it and the tool are rotating with respect to each other. Sometimes

FIG. 13.3. Jiggering process for a porcelain insulator.

FIG. 13.4. Plunging process. View shows plunger after withdrawal from completed product in the plaster mold.

the mold and clay motion is relatively slow and the process is called "jiggering" (see Fig. 13.3). In other cases the tool is often heated and the action is more rapid. This process is called "plunging" (see Fig. 13.4). With either method the clay is left in the mold until enough water has been removed to cause the piece to shrink slightly and release from the mold. The piece is then trimmed, finished, dried, glazed, and fired. The plunging process is usually limited to 14 in. diam by 12 in. high. Jiggering can be used for larger pieces to 22 in. diam but is slower.

13.11 THROWING

The forming of a blank by hand on a potters wheel is known as *throwing*. The method is versatile, and practically any shape that is a product of revolution can be made. It is used primarily for small quantity, nonrepetitive production and for development work since a minimum of tool expense is involved. Since it is costly from the standpoint of time and floor space, development samples furnished by this method should be designed to suit other methods when production quantities are to be required.

13.12 CASTING OR MOLDING

In this process the clays, flint, and feldspar in the pressed cakes are mixed with slightly more water than is required for plasticity and an addition of electrolyte is made to cause deflocculation * of the clay. The slip thus formed has about the consistency of heavy cream and it can be pumped to various parts of the plant.

Plaster-of-Paris molds can be made to form almost any type or shape of piece. The slip is poured into the mold to fill the cavity (see Fig. 13.5). The plaster absorbs water from the slip, which causes the body to cast against the plaster face, building up an ever-increasing thickness of partially solid body. If the piece is to be hollow and of uniform wall thickness, only a mold is used and the excess slip is poured out when the wall has cast to proper thickness. This is called "drain casting." If thick-walled pieces or pieces having variable wall thicknesses are to be made, it is necessary to use a plaster core as well as a mold. The slip casts against both the mold and core faces until it finally becomes solid. This is called "core casting." In either process the piece is removed from the mold as soon as it has shrunk just enough to release. It is then dried, finished, glazed, and fired as for

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* Breakdown of lumps and aggregates.

FIG. 13.5. Casting process for a high-tension porcelain insulator.

plastic process bodies. Pieces up to 80 in. in height and 36 in. in diam are readily obtained.

13.13 DRY PROCESS

The press cakes from the filter press contain about 20 per cent moisture. Only about half this amount is desired in material for the dry process. The reduced amount may be obtained by storing the press cakes under suitable conditions for a few days, and this practice is followed in many plants. The cakes are then granulated and screened for particle size preparatory to pressing.

A more common method of preparing the material mixture is to dry-mix the components, which themselves must be of high purity and proper particle size. The mixing is accomplished in a rotated shallow pan with plows rotated in the opposite direction. The mix is crumbly and disintegrated to aggregates less than 10 mesh in size. Water to the extent of 5 to 12 per cent is added and the material is then ready for pressing.

13.14 DRY PRESSING

This process is suited to forming intricate pieces rapidly and inexpensively. The composition of the body is the same as for the plastic processes but the water is reduced as described in the previous paragraph.

When the base aggregate is put into a steel die and subjected to pressures of from several hundred pounds to several tons per square inch, it becomes coherent and shaped to the contours of the die. Large
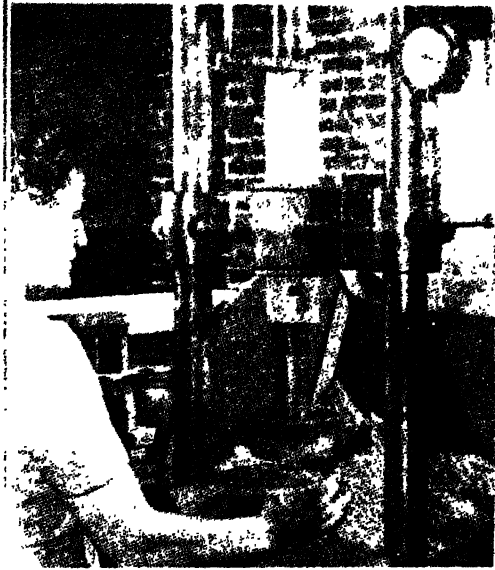
FIG. 13.6. Dry-pressing process for forming ceramic bodies.

numbers of accurately shaped pieces can be made in this manner (see Fig. 13.6). Sizes are usually limited to 85 sq. in. and 12 in. in one dimension by pressing equipment.

The porcelain formed by this process is useful for low-voltage insulators, etc., but it is not acceptable quality for high-voltage insulation. Air is entrapped between the grains in the pressing operation, which causes porosity in the fired piece. Since the granular mass is not sufficiently plastic to permit the body to flow laterally when pressure is exerted in one direction, the shapes that can be successfully formed are somewhat limited.*

* Shape limitations are similar to those described for powder metallurgy (see Chapter 16).

13.15 VACUUM PRESSING

A method has been developed which largely overcomes the objectionable air entrapment in dry-pressed ware. This method consists of using a complex mold or die which can be sealed and the clay subjected to a vacuum before and during the pressing operation. By this method it is possible to make porcelain approaching the electrical and mechanical properties of the wet methods. Shape and size limitations are not affected. The process is much slower, because time is required to effect evacuation of the air. Since time on a costly machine is more expensive than on simple plaster molds, this method of manufacture has little cost advantage over the wet-process methods.

13.16 FINISHING

A number of hand operations are performed on formed ware before the article is in final shape for firing. These operations may be per-

Fig. 13.7. A finishing operation on a dried "green" insulator.

formed before or after drying. Some of these operations are: (*a*) wiping of jiggered ware with a wet sponge to give it a smooth surface; (*b*) removal of fins from casting or pressing operations; (*c*) trimming and rounding of drain holes and top edges of cast ware; (*d*) brushing

pressed ware free of dust prior to firing; (*e*) "sticking-up" of auxiliary parts such as handles on cups; and (*f*) filling in of pinholes or repair of other surface defects.

13.17 DRYING

Ceramic bodies must be dried before firing, otherwise the firing heat will induce cracking. Actually, the drying operation itself must be carefully controlled, especially with the more dense bodies, to avoid this condition.

Drying may be performed by storage in room air, but commercial methods usually employ batch drying or continuous drying in a tunnel kiln. Temperature, air velocity, direction of air flow, and humidity are controlled.

The drying operation takes place in two stages. The first is the removal of liquid water from the surface. Since the water which separates the particles will be drawn to the surface, all the contraction or shrinkage occurs during this stage. The second stage is the removal of water in the pores or capillaries, which must diffuse to the surfaces as vapor. It occurs more slowly. Internal heating of ware of large size or complicated shape by the induction method will therefore reduce the drying time considerably.

13.18 GLAZING AND DECORATING

Although glazing improves the appearance of a ceramic product, its primary purpose on whitewares is cleanliness, sanitation, or improved electrical characteristics and surface hardness.

The glaze is made of a combination of raw materials somewhat similar to the body but having more fluxes. Low-softening-point glazes (cone 010 to 3) are used for artware and semivitreous ware. Medium-softening-point (cone 3 to 10) glazes are used on vitreous china, sanitary ware, floor and wall tile, and some types of artware and stoneware. The high-softening-point glazes are used for hard porcelain, chemical ware, steatite, electrical porcelains, and stoneware.

The glaze may be applied on fired parts or raw parts. The methods of application are spraying, dipping, hand painting, banding (applying bands of applied color or hand painting with a fine brush), and dusting. Spraying and dipping are used most widely. Dipping (see Fig. 13.8) is a fast operation for small ware but requires considerable skill to obtain a uniform coat. Unfired vitrified ware will pick up a heavier coat than prefired ware, and the op-

posite is true for semivitreous ware. Spraying is better suited to large parts and to selective coating. Hand painting is usually restricted to artware and household dinner service; banding for hotel service; and dusting for decorative pieces previously stenciled with a varnish to define the pattern.

Decorative effects may also be applied by decals (decalcomanias)
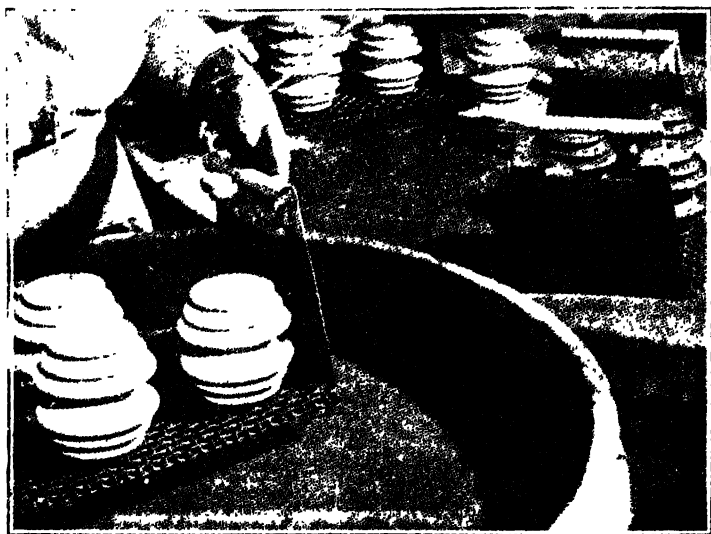
FIG. 13 8.   Glazing insulators by the dip-coat method.

which are a printed design of ceramics usually of several colors applied to paper backing for transfer to the ware. Silk screens may also be used as a pattern for squeezing the ceramic color on the ware by a flexible rubber squeeze. Stencils from sheet rubber or waxed paper board can be used similarly to silk screens. Embossed effects are often obtained by attaching preformed (usually cast) pieces of the same body material. Some simple designs can be created on the ware by stamping with a rubber stamp. Gilt designs and tradenames are added in this manner.

Improper glaze materials or improper firing can cause several types of defects. The most common is *crazing*, which is characterized by fine cracks in the glaze surface. Slivering is a less common defect, which results in flaking of glaze because of excessive compressive stress. *Crawling* is the tendency of the glaze to draw up into nodules, leaving unwetted areas in between. It occurs because of excessive surface tension in the glaze. *Pinholing* is the presence of

small holes in the glaze resulting from carbonaceous material which burns away or from rapid expansion of moisture in the body. *Peeling* is the condition in which the glaze peels off the body.

13.19 FIRING

The firing of whitewares is perhaps the most important operation in their manufacture. It is here that the products on which much time and effort have been expended emerge as a finished salable product. The problems involved are shrinkage and warpage of the parts, uniform heating, proper support so that parts will not lose shape or fuse together (see Fig. 13.9), and degree of vitrification to be achieved.
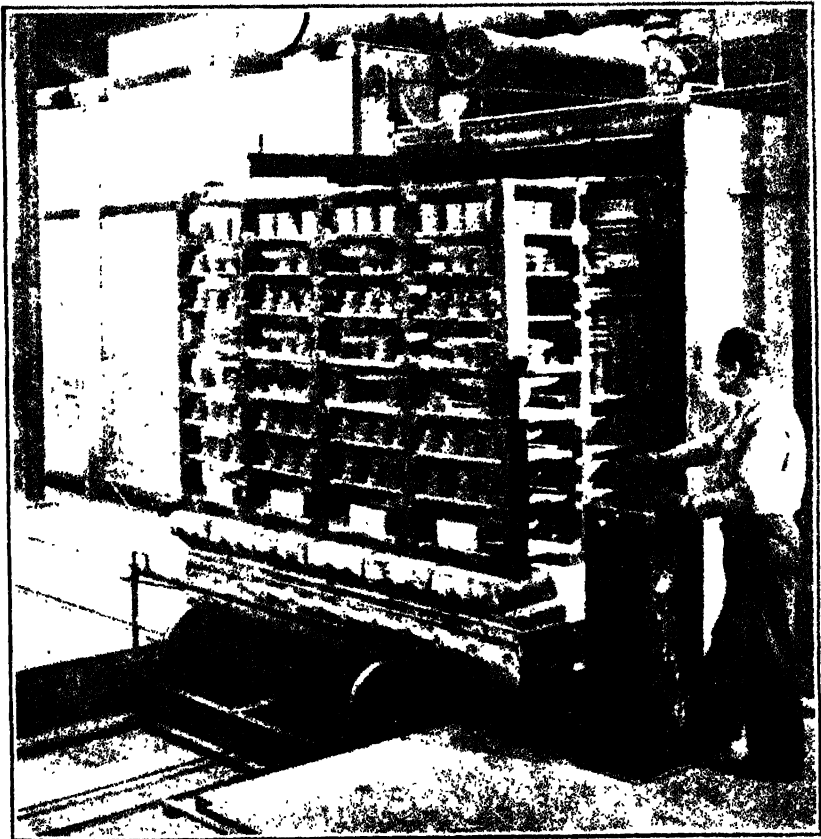
FIG. 13.9. A rack of ceramic insulator bodies arranged for firing and being moved into a batch furnace.

As the ware enters the kiln it contains no more than 2 or 3 per cent water. The first effect of the kiln heat is to drive off this water at from 100 to 300 F. A gentle warm-up period is required to avoid sudden rupture. Next, the chemically combined water in the clays is removed, probably starting as low as 550 F and being completed at 1100 F. Any organic matter also burns out at these temperatures. Thermal lags or advances are experienced during this temperature range as a result of driving off the chemically combined moisture and other crystalline reactions. At about 2000 F the feldspar begins to melt, attacking and dissolving first the clays and then the flints. Complicated chemical and crystalline reactions occur essentially as the result of partial glasslike fusion of the feldspar. The vitrification is complete when further shrinkage of the body does not occur. That is, maximum density is achieved. Further heating serves only to make the body liable to cracking and distortion. Time must be allowed for all but the last of these effects to be achieved, thus a temperature-time schedule is followed for ceramic firing somewhat as is required for metal solution-treatments. Cooling, too, requires a temperature-time cycle to prevent excessive strains as the crystalline form of the silica constituents changes into the lower temperature forms.

13.20 WHITEWARE PRODUCTS

HOUSEHOLD APPLICATIONS A large application for these products is commercial tile for floor or wall use. The applications may be grouped as follows:

(a) *Glazed interior tile,* a nonvitreous variety glazed for cleanliness and appearance. It is nonweathering, has low abrasion resistance, and is available in various colors, sizes, and types. Processes used generally are plastic extrusion or dust pressing.

(b) *Floor tile,* called ceramic mosaics if less than 6 sq in. in size, or pavers if larger. Usually they are unglazed and may contain abrasive for nonslipping qualities. Dust-pressing or plastic processes are used.

(c) *Glazed exterior tile* of the vitrified type for weathering and abrasion resistance. These will withstand freezing temperatures.

(d) *Natural clay tile,* a durable nonvitreous product usually used unglazed. Whereas the former are made from typical whiteware mixtures, these utilize natural or quarry clay, and are often known as "quarries." They are made by the plastic processes.

(e) *Faience tile,* an Italian variety made by the plastic processes and glazed. Either vitreous for outdoor use or nonvitreous for indoors is available.

SANITARY WARE is a second large application for ceramics in construction. Generally, these products are made of vitreous bodies by the slip-casting method, and are glazed for appearance and cleanliness. Some of the simpler parts may be made by dust pressing. Typical parts are water closets, wash basins, and miscellaneous bathroom fixtures.

Other products for use in the home are table service; kitchen ware, such as casseroles, salt and pepper shakers, and baking bowls and dishes; and artware, such as lamp bases and vases. Dinnerware constitutes at least one-quarter of all the whiteware produced. The varieties are many with considerable range in water absorption, mechanical shock resistance, and translucency.

INDUSTRIAL APPLICATIONS Of the industrial applications of ceramic whitewares, electrical applications are perhaps the most extensive and important. There are three general categories: low-voltage insulators, high-voltage insulators, and high-frequency insulators.

Low-voltage insulators are made from "conventional electrical porcelain" and are suited to applications up to 440 volts, although the usual requirements are for 110 volts. Representative properties of these materials are given in Table 13.1. Products for home construction which are used in the unglazed condition are nail knobs for wire supports, cleats, tubes, outlet boxes, surfolets (surface-wiring insulators sometimes glazed for appearance), sockets, and home-appliance resistance grid supports. Low-tension products for outdoor use are usually glazed. Some applications are wire supports for farm electrical fences, lightning arrestors, radio-antennae supports, telephone- and utility-wire supports, and bushings for neon signs.

Cordierite $(2MgO \cdot 2Al_2O_3 \cdot 5SiO_2)$ bodies are a class of ceramics having an extremely low coefficient of thermal expansion over a wide range of temperature. This property makes them very useful for heater radiants, insulator supports for indoor low-voltage heating-wire elements, etc. It is commercially impractical to vitrify these bodies because of their very sharp maturing characteristics and very narrow range before melting. Such bodies are therefore not useful for 'high-voltage insulation or for use under conditions

Table 13.1 Properties of Whiteware Products

(Condensed from Table Published in Bulletin of the American Ceramic Society, Vol. 27 (1948), pages 272-3.)

	Vitrified High-Voltage and High-Frequency Insulation					Low-Voltage Insulation		Chemical Ware		Sanitary Ware
	Elec. Porc., Clay, Flint, Feldspar	Steatite	Zircon	Cordierite	Alumina	Clay, Flint, Feldspar	Cordierite	Clay, Flint, Feldspar	Zircon	
Water absorption	0-0.03	0-0.03	0-0.03	0-0.7	0-1.0	13.0	0-0.7	0-0.05	0-0.05	0-0.03
Bulk specific gravity (g/cu cm)	2.4	2.6	3.6+	2.1	3.7	2.4	1.9	2.8	3.7	2.4
Moh hardness (body)	7.0	8.0	8.0	7.0	9.0	7.0	7.0	8.0	8.0	7.0
Moh hardness (glaze)	6.5	6.5	6.5		6.0	6.5				
Modulus of rupture; unglazed (lb/sq in.)	10,500	19,000	20,000+	9,000	30,000	6,000	7,000	12,000	25,000	5,000
Modulus of rupture; glazed (lb/sq in.)	13,000	24,500	25,000					13,500	30,000	
Tensile strength; unglazed (lb/sq in.)	6,000	8,500	10,000	3,500	20,000		3,000		12,700	
Tensile strength; glazed (lb/sq in.)	7,000									
Compressive strength; unglazed (lb/sq in.)	50,000	70,000	80,000	40,000	180,000	55,000	30,000		90,000	
Modulus of elasticity; unglazed (lb/sq in.)	10×10^6	10×10^6	20×10^6		34×10^6			15×10^6	24×10^6	
Impact strength; unglazed (ft-lb)	1.5+	3.0					2.5	1.4		
Impact strength; glazed (ft-lb)	2.0+									
Coefficient of thermal expansion $\times 10^6$ (0-600°C)/°C	5.2	8.0	3.8	2.7	7.7	5.2	2.7	4.0	4.9	6.5
Max. safe operating temp. (°C)	160	350	350	1,250	1,750		1,250		1,000	
Softening temp. (°C)	1,300	1,300	1,400			1,400			1,400	
Power factor (%) (1 megacycle)	0.90	0.17	0.27	0.45	0.066		0.45			
Dielectric constant (1 megacycle)	5.9	5.8	9.3	4.8	9.2		5.1			
Loss factor (%) (1 megacycle)	5.31	0.99	2.51	2.16	0.607		2.30			
Dielectric strength (volts 1 mil)	250	250	225	175	175		100			
Resistivity (ohm-cm)	10^{13}	10^{13}	10^{13}	10^{13}	10^{18}		10^{13}			
te value (°C)	280	640	680	600	860		780			
Thermal conductivity (cal/cm²/cm/sec/°C)	0.003	0.006	0.006	0.0027	0.0108	0.0043	0.0015	0.004	0.006	

of high humidity. Since only fused silica has as low an expansion but requires a much higher temperature to mature, it is unlikely that a suitable glaze can be made for this type of body. The shape of the pieces to be made of cordierite are generally adaptable to dry-pressing methods, and this method of forming is usually used.

High-voltage equipment makes use of vitrified whiteware bodies. Usually they are glazed for weathering durability and electrical arc-

FIG. 13.10. Assembly of a suspension-type high-voltage insulator to its hardware.

over resistance. Typical products made from conventional vitrified electrical porcelain (see Table 13.1) are suspension insulators (used in strings and suspended free from grounded supports, see Fig. 13.10), pin-type insulators for mounting on a pin fastened to a wood or metal crossarm, transformer bushings, housings for cutouts and coil forms, and spark plugs for combustion engines (see Fig. 13.11). The variety of designs and size of these components is large (see Figs. 13.12 and 13.13).

Zircon porcelain is a special composition type which can be made by any of the methods covered under normal electrical porcelain. Although a range of compositions can be used, the typical composition consists principally of zircon with some alkaline earth fluxes and just enough clay to produce a plastic and easily formable mass. The porcelain thus formed is harder, tougher, heavier, and much
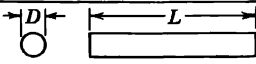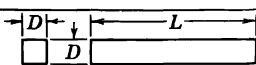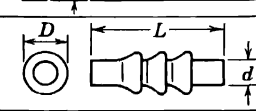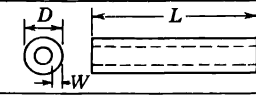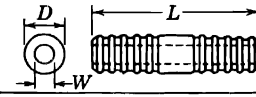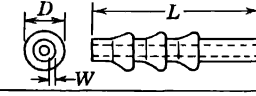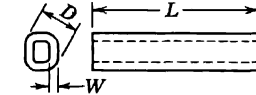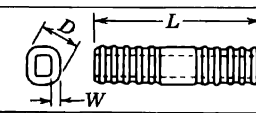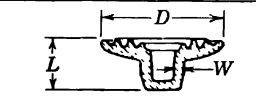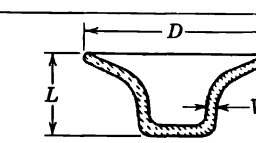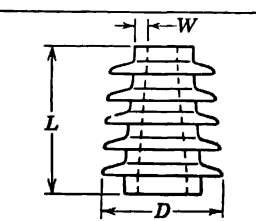
Manufacturing process	Typical shapes	Limiting dimensions						
		L max	D max	W max	D-d max	D/d max	L/d max	d max
Pugging		60″	3″					
Rods		60″	3″					
			5″				6:1	3″
Tubes		60″	13″	1¾″		5:1		
Bushings		60″	13″	1¾″		5.1		
		60″	12″	1¼″	7″	5 1		
		60″	12″	1¼″				
		60″	12″	1¼″				
Plunging		12½″	14″	1″				
Jiggering		10″	22″	1″				
Casting		80″	36″	1¾″				

Fig. 13.11. Typical shapes of insulators.

stronger than normal porcelain. It has higher cost than the varieties already discussed, but its electrical properties make it very useful in special applications. The lower loss factor is of interest in the electronic field. The effect of temperature on its resistivity is of special interest for higher-temperature insulator applications. All ceramic materials have lower electrical resistance at high temperatures than at low temperatures. At some temperature the resistance becomes sufficiently low so that, with a given potential, the energy input balances the radiation and conduction losses of heat, and any further rise of temperature causes a runaway condition. This limiting temperature is very much higher for zircon porcelain than for the feldspathic type of electrical porcelain.

High-frequency applications introduce a number of special requirements for low power loss, high dielectric strength, high resistivity, and retention of these properties to relatively high temperatures. Steatite is the whiteware usually used for these applications, although the oxide ceramics (alumina, rutile, titania) to be discussed later are finding increasing use.

Steatite is a type of ceramic, porcelainlike product composed essentially of talc with just enough clay to produce a plastic mass. This product has high strength and low electrical losses, especially at high frequency (see Table 13.1). It is primarily used for electronic applications. This type of body has a characteristically poor thermal shock resistance, which limits the size of the piece for commercial production to about a maximum of 1 in. in its minor direction. Manufacturing difficulties inherent in the character of the body, as well as the higher price of raw materials, limit this product to specialty uses.

Closely related to steatite is the natural material (block talc) designated "lava." In its unfired state it is capable of being machined and drilled to relatively close tolerances. When fired at about 1850 F it becomes dense and hard, and has almost negligible shrinkage. The electrical properties are similar to steatite, although a little higher in dielectric loss and water absorption is 2 or 3 per cent, which prohibits its use under humid conditions. It is used for vacuum-tube spacers and particularly for experimental models, test parts, and shapes for special equipment where its simplicity of fabrication reduces die costs.

Another material for high-frequency insulation is glass-bonded mica called "mycalex." Powdered glass and mica are mixed with a dilute solution of sodium silicate (or some other binder) and

pressed to the desired shape. After drying, the piece is heated suf-
ficiently to melt the glass, which forms a permanent bond to the
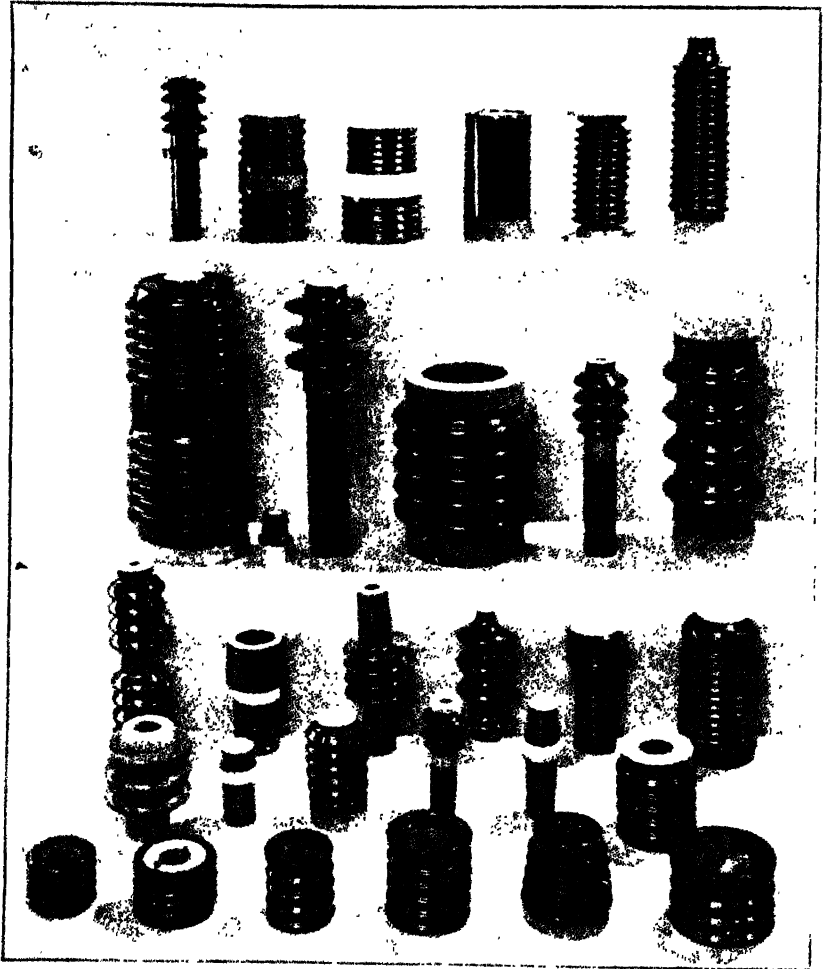
Fig. 13.12. A number of porcelain insulators.

mica. Large blocks or sheets are made in this manner, which can
subsequently be cut or machined to the desired size. For accurate
or intricate pieces, which may also have inserts, hot molding is
used. In this case, the material is preformed roughly to shape by
pressing and is dried. After heating to melt the glass, the shape

is transferred to a hot mold and repressed to the desired shape. Mycalex has very good insulating properties with low loss in high frequency applications at or near room temperatures. Since the matrix glass is soft and somewhat hygroscopic, the product loses its insulating properties at elevated temperatures or under conditions of high humidity.

FIG. 13 13.   A large-size porcelain bushing.

Other uses for whitewares are as balls or lining bricks for grinding mills where metallic particles must not be present, porcelain for dental applications, precision gages having a low-temperature expansion and excellent abrasion resistance, wear-resistant thread guides for looms, etc., nozzles for shot blasting guns dies for pressing, extrusion, rubber molding and casting.

In the chemical field the excellent chemical resistance is employed in stonewares (dark brown from natural clays and minerals), and porcelain crucibles, jars, and components for chemical reactors. Heat-resistant applications include pyrometer tubes, burners and burner tips, and the radiant-heater supports already mentioned.

13.21   PROPERTIES OF WHITEWARES

Specific properties of the typical ceramic materials are listed in Table 13.1 and have been mentioned in connection with the various whiteware products.

Mechanical strength may be measured by tensile, compressive, or flexural tests. For tensile tests, an ASTM Specimen (D116-42) 6 in. long with a straight section $1\frac{1}{8}$ in. diam in the center is most often used. Semivitreous bodies tested in this form with self-aligning gasketed grips usually have load/area values of 2000 to 5000 psi. The steatite and zircon bodies often attain 13,000 psi. Pieces up to 6 or 8 sq in. of cross section may show only one-half the tensile strength of the $1\frac{1}{8}$ in. diam pieces.

Since flexural strength is more conveniently measured with ceramics, strength is often reported as the modulus of rupture. A test specimen 6 x 1 x 1 in. is supported on 5-in. centers and loaded at the center. Finished pieces like hollow tile are tested in finished form with whatever adjustment is needed to adapt the testing equipment. It should be recognized that the outside diameter has more effect on the modulus than does the wall thickness at the critical section, because of the nonductility of porcelain. The modulus of rupture for tubes or solid sections 6 to 8 in. in diam may therefore be $\frac{1}{2}$ to $\frac{1}{3}$ of the values for 1-in -diam specimens.

Porcelain is many times stronger in compression than in tension. Values obtained are 8 to 10 times with ASTM test specimens. The mechanism of compression failure is very complex. For a short column such as the ASTM test specimen (a solid cylinder $1\frac{1}{8}$ in. long by $1\frac{1}{8}$ in. diam) initial failure occurs as shear or spalling. On straight-sided cylindrical tubes of moderate length, failure occurs initially from hoop tension at values much lower than the ASTM test. The porcelain splits longitudinally in thin, wedge-shaped pieces that bow outward into a barrel-like shape and still carry considerable load. A slight outward longitudinal curvature of the sides of relative short columns exaggerates this effect. This results in an even lower strength. A slight inward curvature of the sides greatly increases the strength of short columns. With proper design of the hardware parts and bearing surfaces of the porcelain, strengths approaching those of the ASTM specimen (in pounds per sq in. of cross section) have been obtained on moderate sections. As the section size increases, the unit strength decreases, due probably to the inequalities of load distribution. Long columns, on the other hand,

fail by buckling, thus inwardly curving of the side would decrease the strength.

Torsional strength is seldom a factor in electrical porcelain applications, since designs which meet tensile and cantilever requirements usually have inherently ample torsion strength. Areas to receive torsion loads are usually sanded (unglazed special bands added to the glazed piece and fired with it), and their torsional strength is a function of the depth and diameter of the sanded area.

Impact strength is measured on the charpy machine, but the specimen is larger than a metal specimen and contains no notch. Cylindrical specimens 6 in. long and with diameter of 0.5, 0.75, or $1\frac{1}{8}$ in. are usually used. Impact values are then reported in ft lb/sq in.; 0.52 to 0.88 for vitrified ware, 0.80 to 0.95 for dense stoneware, and 1.2 to 2 for steatite and high-titania. The dry-process wares will have values 30 to 40 per cent less than these wet-process materials.

Other properties measured are elasticity, water absorption (by gain in weight after 24 hr immersion, or vacuum immersion. For dense bodies dye penetration is more accurate), expansion resulting from absorption of moisture, thermal expansion, thermal shock resistance (usually by alternate immersion in water or other media at two extreme temperatures), heat conductivity, hardness/abrasion resistance, resistance to chemicals, and the electrical properties such as dielectric strength, dielectric constant, power factor, loss factor, and volume resistivity and flash over (see Chapter 10).

13.22 DESIGN CONSIDERATIONS

Glazing. The kind of glaze used has a marked relation to the mechanical and thermal characteristics of porcelain. Compression glaze, one that has a lower coefficient of thermal expansion than the porcelain body, should always be used to obtain optimum performance. A neutral glaze with the same coefficient of expansion as the porcelain gives a slight increase in physical properties over unglazed porcelain. This is because of the greater smoothness of the surface. Tension glaze, one whose coefficient of expansion is greater than that of the porcelain, should never be used. Not only will it greatly reduce the strength of the porcelain, but the glaze will eventually craze, especially if under appreciable tension.

Firing Surfaces. In order that the porcelain shall not stick to the supporting structure on the kiln cars, it is necessary to provide an unglazed surface on which the piece rests. In many cases this unglazed surface can be hidden by subsequent assembly operations, as

is done with the unglazed head of a suspension insulator shell. If the unglazed surface is not hidden it can, in many cases, be located where least noticeable and where it will in no way affect the performance. Tubes and bushings with a height not exceeding 6 times the outside diameter of the firing foot are steady enough to stand in the kiln, but longer pieces than this must be hung. This is more expensive in material, kiln space, and labor, since such pieces must be provided with a firing head, which takes up additional kiln space and must be cut off after firing. The length of a porcelain piece that can be hung depends upon its volume with respect to the area of the section that supports that volume. Volumes up to 160 cu in. per sq in. of supporting area can be fired in this manner. Designs longer than 50 or 60 in. should be avoided if possible.

Shrinkage. The combined drying and firing shrinkage of porcelain runs from one-seventh to one-eighth. This means that a piece formed completely in the plastic state with no subsequent machining is between 14 and 17 per cent larger than it will be after firing. The shrinkage in the kiln itself runs from one-tenth to one-twelfth. At the peak of the firing cycle the material passes through a sticky, semi-plastic state during which it can be deformed or bent by pressure to a marked degree without fracture. The thickness of section, ratio of diameter to height, and section shape therefore all introduce variables. The shrinkage is not uniform in all directions. Long pieces that stand in the kiln tend to shrink more in length than in diameter, whereas long, hanging pieces may shrink less in length than in diameter. Similarly, large standing pieces tend to shrink less in diameter at the bottom than at the top. Increasing wall thickness to the point where it would have sufficient load-carrying capacity to prevent slumping in the kiln may make it difficult to obtain complete and uniform vitrification; consequently, a certain amount of slump is to be expected.

Warpage also has a great effect on tolerance requirements. It occurs as bow or crookedness in the length and sometimes as a slight egg-shape instead of roundness in cross section. Bow varies in relation to the slenderness or length to diameter ratio—the more slender the piece the greater the tendency to bow. The effect must be considered in determining permissible tolerances or by allowing liberal clearances between the porcelain and other parts.

Tolerances. It has been found through years of experience and by proper analysis of the probable shrinkages that a standard tolerance of plus or minus $\frac{1}{32}$ in. per in. or fraction thereof on all dimensions

will permit practical commercial manufacture with reasonable cost for wet-process porcelain. Dry-press-process tolerances of about 2 per cent or 0.020 in. per in., are practical.

Although assembly operations may be simplified by more rigid porcelain tolerances, this is generally obtained at the expenditure of increased labor costs during porcelain manufacture. It is therefore recommended that procelain parts and their companion hardware and other parts be designed to allow for the standard tolerance if at all possible.

Where close or critical tolerances must be specified the cost is increased, but generally a tolerance of ±2 per cent with a minimum of ±0.020 in. can be held on wet-process parts. Dimensions between unglazed parts can generally be held to ½ of these figures. Dry-process porcelain parts can be made to ±1½ per cent with a minimum of ±0.015 in., although dimensions affected by die filling (across parting line) or by die wear must have 50 to 100 per cent greater tolerance.

Grinding. Because porcelain is harder than most types of glass, grinding in the fired state is the only means of truing up mating surfaces after firing. The closer the required tolerances the more expensive the operation becomes, but ±0.001 in. can be obtained if needed. A group of 0.020-in. to 1/32-in. bosses for establishing the mating surface offer economy over grinding a full surface where they suffice. The costs should be carefully considered in each design against the cost of providing take-up in the hardware parts or gaskets in the final assembly operations.

Draft. Since molds and any cores must be removed from the wet-process parts, a draft of at least 0.015 in./in. must be provided, although 1/32 in./in. is preferable. External draft on products of revolution can be readily removed if undesirable, but removal of internal draft is more difficult and expensive and should be incorporated into the final shape where possible. Where machining operations are used, the green part must be capable of resisting the loads involved without undue distortion. This usually limits the minimum diameter of a cylindrical member to 1/6 to 1/7 the length.

Dry-pressed parts can be made with plain straight outside surfaces and holes.

Fillets and Radii. Generous fillets are required to reduce chipping hazard at external corners, to reduce stresses, and to aid flow of material in forming. Where these radii are applied by the mold to adjoining sections, the minimum radius should be ¼ in., and values of

⅛ the adjoining component should be used for components above 2 in. dimension. In machining, the minimum radius may be $\frac{3}{32}$ in., and ⅛ of the size of components above ¾ in. dimension. External radii to avoid chipping should be $\frac{1}{16}$ in. minimum, and a $\frac{1}{32}$ bevel or chamfer is generally desirable.

Wall Thickness. Sections should be kept as uniform as possible without abrupt variations to provide uniform drying, firing, and shrinkage. Wet-pressed parts should be at least ⅛ in. thick and generally not more than 1 in. in thickness.

Ribs. Protruding ribs or fins should be spaced apart as much as they are wide or deep. A radius on the top of ribs is advantageous. Ribs are desirable for strengthening relatively light walls.

Grooves. Recessed grooves and shallow grooves are preferable to full-length grooves and deep grooves respectively to limit distortion.

Holes. Holes as small as 0.010 in. are produced in thin parts, but $\frac{1}{16}$ in. diam or over is preferable for economy. Walls between holes should be at least one-half the hole diameter and never less than $\frac{1}{32}$ in. Holes should not be closer than ⅛ in. to edges. Differential shrinkage tends to cause holes to be somewhat elliptical. For glazed holes ± 0.012 in. up to 0.6 in. diam and 2 per cent for larger holes is a common tolerance. On unglazed holes one-half these tolerances are common.

Shrinkage also affects hole spacings. A tolerance of ± 1 per cent and not less than ± 0.005 in. can be held. Generally it is desirable to elongate holes in the direction of spacing to provide for easy assembly, the amount being at least twice the tolerance on the distance between hole centers.

Threads. Since it is impractical to mold threads in ceramic parts, they are machined in the green state. Although 3–48 threads are sometimes obtained, 6–32 should be considered minimum, and preference given to coarse threads. Four to eight threads in contact should be the maximum for through holes, with 6 preferred. For blind holes, 12 threads should be provided and 8-thread engagement planned for ideal fit. External threads may be cut sharp but are more durable if an extended pitch and internal and external fillets can be used. Greatest economy is obtained by threading full length rather than part length or to a shoulder.

Lettering. Block letters with raised characters on a depressed surface are preferred for dry-pressed parts. Other ware is generally marked with ceramic ink on unglazed portions.

Joining Materials. Portland cement has been found to be the most satisfactory bonding material for general use. To assure consistent performance the cement is specially selected from the product of certain approved cement mills. For thin joints it is used neat, whereas for wide joints it is mixed with sand. The major disadvantage of this cement is the time required for setting.

Sulfur cement is used where quick setting is essential. This solution is not applicable if the joint is exposed directly to oil or to abnormally high temperatures, however.

Lead-antimony alloys (sometimes inaccurately called "type metal") are employed when the joint will operate in oil or at higher than normal atmospheric temperatures. These alloys are expensive and generally require preheating the porcelain and hardware.

Many other materials, too numerous to mention, are used in limited quantities to meet special requirements.

Sand bands, made from unfired special porcelain particles under controlled conditions, are secured by glaze to the porcelain at the locations desired for joints. Such sand bands are fired to the porcelain piece and provide, by far, the best cement grip. The size and location of these bands depend upon the type of loading and the shape of the parts, since cement is much stronger in compression and shear than it is in tension.

Bricks

13.23 BUILDING BRICK

Building brick are generally made of natural clays of low P.C.E. (Pryomatric Cone Equivalent) values, and they could be classed as low-grade refractories. These materials are generally chosen because of their easy workability, moderate temperature of firing, low cost, availability, and consumer preference as to fired color. The manufacturing plant is generally located very close to the clay mine, and the clay is used substantially as dug without purification or compounding with other materials. Since the product is highly competitive, only the lowest-cost methods of forming are used. Generally, the clay is mixed with water to a plastic state and extruded in a column that is wire-cut crosswise to the desired size. Occasionally the dry-pressing process is used.

13.24 REFRACTORY BRICK

The better grades of building brick and the refractory brick shapes, where accuracy of sizing is important, are generally made either by dry pressing or by repressing the plastic extruded shape to produce best dimensional fidelity. The casting process, common in the porcelain and whitewares industry, is seldom used except for special shapes. For a relatively small proportion of special superrefractories, the material is melted in an electric-arc furnace and cast into shape in a manner similar to metal casting. In general, however, the process of manufacture of refractories is very similar to building brick except that sizes, accuracy, and temperature of firing differ with the ultimate use of the product and the maturing temperature of the raw material.

The classification of refractories depends on the temperature the material will withstand under load, the resistance to disintegration under conditions of sudden temperature changes, and resistance to the corrosive action of various slags. Building brick, as for other fired clay products, are inherently resistant to fairly high temperatures, and a few types may warrant a classification slightly higher than low-grade refractories. "Normal-duty" refractories are those used for linings of small furnaces, kilns, etc., where temperatures are not too high—probably 2300–2400 F—and there is little slag erosion. "Heavy-duty" refractories are the types generally used for large furnaces and kilns where higher temperatures, up to possibly 2800 F, or higher load concentrations, at somewhat lower temperatures, are encountered. Slag-erosion conditions may be more severe for heavy duty than for normal duty but if the conditions are severe the class known as "super-duty" refractories are used. The classifications mentioned above are derived from proper choice of clay and the process of manufacture. The clays may be either highly siliceous (acid type), or they may be a neutral type containing somewhat higher alumina (Al_2O_3) than the molecular proportion for normal clays. Silica brick are made of at least 95 per cent SiO_2 fired at a time-temperature to convert substantially all of the SiO_2 from quartz to crystobalite or tridymite, which have better resistance to temperature changes. Although usually classed by themselves, silica brick may be considered as falling in the classification known as "superrefractories." Refractories in this classification are generally of the "oxide-ceramics" type rather than of clay compositions. They are designed for specialized severe service and may be of the "acid" type

(SiO_2, SiC, zircon, etc.) or "basic" type (Al_2O_3, "magnesite," chromite, etc.). The name "magnesite" is a misnomer, since the mineral Magnesite is $MgCO_3$, whereas the "magnesite" refractories are composed of dead burned MgO.

Oxide Ceramics

13.25 OXIDE CERAMICS

All ceramic compositions are composed of oxides and mixtures or reactions of oxides. Some types, such as porcelain, whitewares, etc , derive their strength, compactness, and other properties from the formation of a glassy bond or matrix formed during the firing operation. The term "oxide ceramics" has been coined to describe a type that is essentially glass free and is generally fired at higher temperatures than the older types. It derives its strength and compactness from a sintering cohesion of the crystalline particles directly, rather than through a glassy bond. Such bodies can be made so compact as to be impervious to dye or even to very high vacuums. Since SiO_2, B_2O_3, P_2O_5, etc., are the more common glass-forming oxides, they are usually very low or absent from this type of ceramics. Such bodies differ from the glass-containing ceramics in several properties. Because there is no glass to soften and flow, the bodies are generally highly resistant to deformation at temperatures up to nearly the melting point. Because glass loses its resistance with elevated temperature and becomes a conductor when molten, these glass-free bodies generally have much higher resistance and lower electrical losses at elevated temperatures.

In general, the forming of ware of oxide ceramics is similar in process to those of porcelain except that certain techniques are required because of their relatively low degree of plasticity in the absence of clay. Finer grinding of the raw materials, the addition of various plasticizers and binders, and rigid adherence to predetermined techniques allow the formation of ware by the processes of casting, extrusion, and pressing to somewhat closer tolerances than for typical whitewares. Because of their refractory nature, a higher firing temperature is generally required. A large number of composition types have been made to fill a variety of needs. Without attempting to provide a complete listing, a few examples are given to indicate some of the fields covered.

13.26 ALUMINA

Automobile spark plugs have utilized whiteware minerals of the sillimanite type ($Al_2O_3 \cdot SiO_2$) for many years. The rigorous requirements of the aviation industry, and particularly the military aviation, led to the development of nearly pure alumina (Al_2O_3) bodies for spark plugs. The higher heat conductivity keeps the plugs cooler and minimizes pre-ignition of the gasoline-air mix. The high electrical resistance at high temperature allows more energy of the spark to be transmitted to the arc gap instead of being dissipated through the insulator. The high strength and resistance to thermal shock prolong the life of the spark plug. The use of alumina bodies has extended to the electronic field because of its characteristics of low loss in a high-frequency electrical field coupled with high strength and thermal shock resistance (see Table 13.1). The resistance of the crystalline body to deformation at very high temperatures—approaching its melting point of about 2000 C (3632 F)—has made alumina bodies of interest for certain refractories applications.

13.27 OTHER OXIDES

For resistance to still higher temperatures it has been necessary to use other oxides having high melting points. Thoria, zirconia, beryllia, and calcia have been used successfully. Each has specific advantages and disadvantages. The choice of material depends on a careful analysis of the problem and the properties of material considered critical for the application. As examples, CaO is not a very strong material and disintegrates under humid conditions but is excellent for platinum melting because of its inertness towards metals. Zirconia is a very good insulator when cold but if externally preheated to about red heat becomes sufficiently conducting to be used as a resistor element. Bodies containing mainly a single oxide like beryllia or zirconia and small additions of oxides of boron, calcium, magnesium, silicon, or titanium have shown good, high-temperature strength and offer promise for gas turbine and rocket applications.

13.28 TITANIA

Titania and various compounds of titanium oxide and alkaline earth oxides deserve special mention. These bodies are not highly refractory although they require about 2400–2600 F to mature properly. Electrically they are all particularly interesting because they are characterized by high dielectric constants (normally designated by "K").

The "*K*" value can be controlled within fair limits over a wide range from below 85 to over 7000. Since most ceramics have "*K*" values between 5 to 10, these bodies are many times more effective as capacitors for a given design. Most of the compositions vary in "*K*" value with temperature. Most of them have a sharp peak at some specific temperature. To some extent, the relative size and location of this peak on the temperature curve can be regulated so as to produce a positive or negative temperature coefficient at some specific temperature range. Some of the compositions display very strong piezo-electric properties under certain conditions.

13.29 FERRITES

Another interesting type of oxide ceramics is the class known by the coined name of "Ferrites." The name is derived from the property of being ferromagnetic although containing no metallic iron. Some of them do not even contain iron oxide. The field of usefulness is as yet only little known. Often the materials have high magnetic permeability, reasonably high saturation, and can be made to have high resistance (see Chapter 6).

13.30 CERAMICS AND METAL COMBINATIONS

Sintered combinations of ceramics and metals are variously designated as cermets, ceramels, metamics, metallo-ceramics, and cerametallics. They are an attempt to impart the high refractoriness of ceramics with the toughness and thermal shock resistance of metals. The field is very new and only a few of the potentially large number of materials have emerged from the development stage. Examples are (1) combinations of aluminum oxide and chromium that have tensile strength of 20,000 psi at 2000 F, and (2) hot-pressed tungsten carbide with nickel or cobalt additions.

Refractory coatings for protecting metals from oxidation, corrosion, and erosion at high temperatures are also finding applications. They are usually made from special glass frits of high expensiveness and with the addition of oxide ceramic materials such as alumina, zirconia, magnesia, and oxides of nickel, cobalt, and chromium. They may be applied by usual methods, 0.0015 to 0.004 in. thick, with the thinner coat preferred for avoiding blistering and resistance to thermal shock. Coatings that combine metals with oxide ceramics are a new development. Cobalt-silicon carbide, nickel-magnesia, and aluminum-alumina are typical combinations undergoing experiment to provide improved heat distribution and improved life.

Glass

13.31 MANUFACTURE OF GLASSES

As a general classification, glass differs from other ceramic compositions more in its method of forming than in ultimate composition. The previously mentioned ceramic wares were formed to shape before firing and then fired to a temperature and for a sufficient time to cause the reactions to proceed to a point where strength, durability, and desired properties are obtained while maintaining substantially the original shape. In the production of glassware the mixtures of raw materials are put into a suitable furnace container and melted to a fluid state. The reaction is carried substantially to completion at a high temperature. The mass is then cooled to a lower temperature where it becomes more viscous and can be worked into the final shape. The material can be reshaped at any time by reheating to the softening range of the glass which is a much lower temperature than its original melting temperature. Except for grinding special surfaces, drilling holes, etc., glass is generally in its finished shape and form on cooling.

Since glasses in general cannot be held too long in the temperature range of workability without danger of devitrification, and since the process of forming requires fairly rapid cooling as soon as the pieces have acquired the desired shape and before they deform to some undesired shape, strains are set up in the glass due to the relatively large thermal gradient in the glass as it "sets." These strains must be annealed out of the glass to prevent breakage. This is accomplished by putting the ware into a special furnace called a "lehr," where the glass is brought up to just below its deformation temperature and then cooled very slowly to prevent the reintroduction of strains.

Various manufacturing techniques are utilized to shape glass into usable forms. Sheets and plates are made by drawing the molten material through rolls and then carrying it between or over rolls until sufficiently cooled. The Colburn and Fourcault processes are typical. Wire glass is made by rolling wire mesh into the soft glass. Figured or Florentine glass is made by rolling in the imprint from a roll. Glass brick, table articles, and similar products are made by pressing in a mold. Some water-glass shapes and similar articles are made by impact extrusion. Bottles, lamp bulbs, and necked containers are made by blowing slugs into outer molds, sometimes in multiple operations. Tubing is made by blowing a hole through a molten glass mass and

drawing the tubing onto a rotating cylinder. Glass fibers are similarly drawn to a thread of glass from a rod heated to plasticity by throwing the thread over a rapidly rotating drum. Fibers as fine as 0.005 mm (0.00022 in.) are made continuously. They may be matted for thermal insulations, matted for forms in plastic components, and woven into tapes, sheets, cloths for plastic inserts and electrical insulations, or as drapery and clothing materials.

Special products include safety glass, either of laminated sheets cemented together with a plastic or of tempered plate glass; double glazing units with a sealed air space between, such as Thermopane; photosensitive glass, which can be exposed to ultraviolet light and then developed to positive images of the prepared color; electrically conductive glass, which opens new possibilities for electric heaters, appliances, and de-icers; cellular glass, made by mixing carbon with the glass, which results in a foam having a myriad of bubbles when heated above the softening temperature; and silica aerogel, a granulated insulation.

13.32 COMPOSITIONS

There are innumerable compositions of glasses, and the classifications are varied and often overlapping. One method of classification depends on the end use; i.e., optical, chemical, tableware, bottle, window, etc., glass. These may often be substantially similar in composition but vary in purity, perfection, or method of manufacture. Another method of classification is based on general composition types; i.e., lead glasses, borosilicate glasses, soda-lime glasses, flint glasses, phosphate glasses, and fluoride glasses. The latter classification has more meaning to the layman and is therefore more common.

13.33 SODA-LIME GLASS

This type is the most familiar glass, since it is used for window glass, plate glass, bottles, containers, electric light bulbs, glass "brick," etc. It is essentially a melt derived from Na_2O (from soda ash), CaO (from limestone) and SiO_2 (from sand). Although still a fairly "soft" glass, it has a generally higher softening temperature than lead glasses, lower density, lower refractive index, and much lower cost. It is usually more durable than the lead glasses. In some, potash replaces part of the soda and the classification blends towards "Potash glasses." Such glasses are often used for tableware as they tend to have a higher luster than the corresponding soda

glasses. Glasses containing lime as the chief stabilizing ingredient are also used for optical purposes. They are often called "crown glasses," a term that originated because this glass, used for hand-blown windows, had the shape of a King's crown in one stage of manufacture.

13.34 LEAD GLASS

Lead glasses contain substantial amounts of lead oxide as the fluxing ingredient. They are characterized by low softening point (soft glass), high density, high refractive index and consequently high luster, relatively high cost, and generally moderate to low durability. Their ease of workability often offsets the increased cost. The variants are useful for cut glass, tubing for forming, and electrical seals. They are also used for optical purposes where they are commonly referred to as "flint" glasses, a term originating from the use of flint as a source of silica in them.

13.35 BOROSILICATE GLASS

These glasses contain varying amounts of boric oxide, which is usually added as borax, along with soda and silica. Depending on the relative amounts of each constituent, these glasses may be either "soft" or "hard." The greatest fields of usefulness for this type of glass is in the range of lower soda and higher SiO_2 where the glasses are "hard." The effect of the boric oxide is to make the glasses more workable with higher silica content than they would otherwise be, to decrease the coefficient of expansion, and to increase the chemical durability. Such glasses are used primarily for "heat-resisting" or, more properly, thermal shock-resisting qualities and chemical durability. The trade name "Pyrex" is a familiar example of this type of glass. A special grade having a low coefficient of expansion is known by the trade name "Vycor."

13.36 PHOSPHATE GLASSES   –

The glass-forming properties of P_2O_5 are used to replace most or all of the SiO_2 in some special glasses. Phosphate glasses also vary compositionally in their other ingredients. They can be made either "soft" or "hard" and are generally used for special purposes to utilize their property of high radiation transmission of wavelengths extending from well down in the infra red to well up in the ultra violet.

Porcelain Enamels

13.37 ENAMELS

Ceramic enamels are usually referred to as "vitreous enamels" or "porcelain enamels" in order to distinguish between this type and the organic vehicle and resin type of enamels. Ceramic enamels are composed of special types of glass compositions which are formulated to soften and flow at a relatively low temperature and have an expansion coefficient similar to that of the metal to which they are to be applied. They may be colored or opacified as desired.

13.38 ENAMELING PROCESSES

There are three general processes for the application of vitreous enamels. The "wet-process" method includes the general technique of melting the glass composition and quenching the molten composition in water. The product so formed is called "frit" and is relatively friable and easily ground. It is mixed with clay, water, electrolytes, and any opacifier or color desired, and milled in a ball mill to the desired degree of fineness. Only sufficient clay is used to act as a suspending agent in the water suspension and as a bonding agent for the dried coating. The suspension is applied to the metal by dipping, slushing, or spraying. After the water is dried out of the coating, the metal object is put into a hot furnace for the few minutes necessary to raise the temperature of the piece to the melting temperature of the glass so that a continuous coating of glass is formed that bonds to the metal base. Signs, ranges, refrigerators, and kitchenware are enameled in this manner as are resistors, tile, and other thin-gaged metal products or small iron castings.

The "dry-process" method is used for heavy cast-iron ware such as sinks and bathtubs, where the heat capacity of the metal part is sufficient to cause melting adhesion of the dry-milled frit as it is dusted onto the *hot* piece. This method is preferred on heavy ware because the time of heating is long and the rate of heating of the sides is more rapid than for corners or heavier sections. If the enamel were applied before heating, some parts of the piece would be hot enough to allow the molten glass to run before other parts were hot enough to fuse the glass.

A third method of application is often used on wires and consists of drawing a continuous wire through a molten bath of glass.

The temperature of the bath and speed of the wire are regulated to control the thickness of glass which adheres as the wire is withdrawn.

13.39 BASE-METAL COMPOSITIONS FOR ENAMELING

Cast Iron. A typical cast iron for porcelain enameling has the following composition:

	Per Cent
Carbon	3.25–3.60
Graphitic	2.80–3.20
Combined	0.30–0.60
Silicon	2.25–3.00
Manganese	0.50–0.70
Phosphorus	0.60–0.90
Sulfur	0.05–0.10

The desired structure is that of a gray iron with 52 to 58 per cent pearlite, 2.6 to 8.4 per cent steatite, 2.8 per cent graphite, 0.15–0.23 per cent manganese sulfide, and 31 to 44 per cent ferrite.

Relatively uniform sections are desired for uniform heating, and sharp edges should be avoided since enamels tend to run away from them, leaving a dark line where the enamel is thin. Surfaces should be blasted clean with sand or grit, leaving a slight roughening for enamel adherence.

Sheet Iron and Steel. Enameling sheet iron has the composition 0.013 per cent C, preferably in carbide form, a trace of silicon, 0.02 sulfur, 0.0075 phosphorus, and 0.023 per cent manganese. It is the best stock for porcelain enameling since it has the least tendency to blister, fishscale (small chips or scales which pop loose when the ware is cooled), or boil. It is used chiefly for tabletops, refrigerator linings, signs, and other large ware or drawn parts where reduced liability of defects is important.

Good enameling steels are somewhat less expensive than the enameling irons because of the longer period required to refine the latter. Two common grades are:

	Per Cent	*Per Cent*
Carbon	0.05	0.14
Silicon	Trace	Trace
Sulfur	0.035	0.043
Phosphorus	0.005	0.036
Manganese	0.30	0.45

Sulfur and phosphorus have little effect on enamel blistering. Silicon tends to produce this effect, but manganese counteracts the tendency up to the point where it induces crazing. Increased carbon content requires use of softer enamels if blistering is to be avoided. Chrome, nickel, vanadium, molybdenum, and cobalt do not cause blistering, but nitrides do.

In the preparation of sheets for enameling, oil, rust, and scale must be removed, and the surface must be smooth but not polished. The operations used are annealing to remove strains, and scaling, chemical dipping, or pickling to clean the ware. Shot blasting is used only on heavy-gage stock (above 14 gage) The use of a nickel dip (dip into nickel double salts, $NiSO_4 \cdot (NH_4)_2SO_4 \cdot 6H_2O$) has also become popular after pickling, and is itself followed by a rinse and neutralizing dip. The nickel "flash" of 0.4 to 0.08 g/sq ft improves the adherence of white ground coats and tends to eliminate the fishscale and copperheads (reddish-brown spots of iron scale or oxide) in the blue cobalt ground coats.

Best adherence of enamel on sheet irons and steels is currently obtained by using a blue ground coat, following this with one or two coats of the colored or opacified (white) coats. The early (white) opacifiers were tin oxide. Successively they have been replaced by antimony, zirconium, and titanium oxide opacifiers. Antimony types are available in both nonacid and acid resisting, the latter suited as a cover coat only. Zirconium types are all nonacid resisting. Titanium types are acid resisting.

Much work is being done on one-coat white systems, that is, white ground coats utilizing titanium oxide opacifiers. Special types of steels are required and several are available from suppliers. One contains titanium at least 4 times the weight percentage of carbon to eliminate free carbon, but since this steel is of the killed type it does not offer as good a surface as typical rimmed enamel irons. Shock resistance of coatings is good, probably as a result of both the base metal adherence and the thin coatings possible with the one-coat system.

Development is also directed toward lower-temperature firing enamels. Although they are not necessarily intended as replacements for 1500 F enamels, they offer enameling of objects heretofore not feasible and at temperatures as low as 1300 F. Ground coats are available which give suitable adherence on steel previously given a nickel dip. Cover coats can be applied over them. One applica-

tion has been architectural trim with acid resistant semimatte finishes of light and dark colors.

Design of sheet ware for porcelain enameling generally should allow greater stock thickness as the width increases. Sections which may buckle or "oil-can" should be avoided, and ribs, beads, or ⅜ in. min flanges should be used with large flat sections to maintain flatness of sections. Sharp edges should be avoided where coating is desired, and, in this respect, corner radii of at least 3⁄16 in. are preferred over sharp corners or edges. White cover coats must usually be masked or wiped from sharp edges to avoid chipping in handling. Holes should allow 1⁄16 in. to ⅛ in. for build-up of enamel. Allowance for edges should be 0.050 in., and ⅛ in. for fit of corners for the same reason.

Abrasives

13.40 ABRASIVE PRODUCTS

Although abrasives are seldom used as or in an industrial product, they are a useful component to manufacturing operations. Their kinship to other ceramics merits their mention here.

Abrasive materials are marketed in three general forms: (1) in bonded wheels, discs, stones, etc.; (2) as a coating on paper and cloth; and (3) as loose grain in dry or paste form.

Bonded products are made in a number of standard shapes and sizes, with a number of different grain sizes, and with one of several bonding agents. The most satisfactory general bond for long wear is a vitrified ceramic made of clays, feldspar, flint, and sometimes frit mixed together with the grain. Resin bonds produced by pressing at high (1000 to 4000 psi) pressures and curing are used at high surface speeds and produce a smooth grinding action. Hard vulcanized rubber is also used as a bond for high-speed wheels which produce smooth action because of the cushioning effect of the rubber. Shellac bonds are less frequently used but are excellent for bending pressures (side grinding) because of their elasticity.

The abrasives applied may be diamond dust, boron carbide powders, silicon carbide, fused alumina, corundum (natural aluminum oxide), and silica. Diamond is most used for cutting gems, hard minerals, or carbide tools; silicon carbide for low-strength metals and the nonmetals; fused alumina for hard materials and most steels; corundum for rough grinding of malleable iron; and silica for grinding stones.

Selection of abrasive wheels should observe these general rules. Grit size should be large for fast removal of stock or ductile materials, small for fine finish or hard, brittle materials. Hard minerals are best for soft materials and vice versa. Short arc of contact indicates use of harder grit. Harder grades are also desired for faster work speed and are used more easily by unskilled workers or on machines in poor condition. Elastic or rubber bonded wheels are best for wheels to be subjected to bending, wheels of thin section, or for highest finish. Vitrified wheels are suited to fastest cutting at speeds under 6500 ft/min.

Fused alumina, emery (mixture of corundum and magnetite) and garnet (natural silicates of alumina, calcium, magnesium, manganese, iron, or chromium) are most used for coated products. The first two are extensively used on cloths for finishing operations in the metal-working industry. The latter is used for leather working, automobile polishing, and hardwood "sanding." For soft woods a flint grain is used, since the wood dust soon coats the grain, and no breakage of the grain to produce new sharp edges occurs as with other uses of the coated abrasives.

Loose abrasive grain may be used in an air blast, as for cleaning building stone, or with a lubricant, as in plate glass and lens-polishing operations. Grains are available from 8 to 275 mesh for general usage, and for special purposes fine powders to 2600 mesh are produced.

13.41 CONCLUSION

This chapter has dealt with a very broad yet very interesting field. The materials used have been treated in a general way, since the engineer will usually utilize the services of a ceramicist, in his or the vendors plant, in making specifications. Similarly, the processing operations have been covered in only enough detail to illustrate the techniques available and to highlight the design possibilities. In this way the engineer is provided with the necessary background knowledge to work with those who specialize in this field. More particularly, it is hoped this review will illustrate the attractive possibilities of ceramics which are only beginning to be exploited in the capital and consumer's goods industries.

Review Questions

1. Name the typical raw materials used for ceramic whitewares. What proportions of each are used for porcelain products?

2. What are the two basic ceramic manufacturing processes?

3. Describe briefly the five methods of forming ceramics products, and indicate whether they apply to the wet or the dry process.

4. Explain four types of defects which may occur in glazing.

5. Pick typical products for each of the types of whiteware materials in Sec. 13.20.

6. Name four advantages of ceramics and five disadvantages.

7. Describe five typical design considerations for ceramics parts.

8. How do oxide ceramics differ from clay types in cost, properties, and tolerances of manufacture?

9. What distinguishes glasses from the whiteware ceramics? Which type is in widest use commercially?

10. What composition is best suited for enameling iron and steel parts formed from sheets? What composition for enameling cast irons? How do enameling processes differ for cast irons and sheet steels?

11. What type of opacifiers are available? How are they usually used and applied in high-quality sheet ware?

12. Describe several design considerations for porcelain enameled ware.

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14 MISCELLANEOUS NONMETALLIC MATERIALS

Preceding chapters have covered the structural nature, the properties, and the applications of the materials that comprise the bulk of all industrial products. Auxiliary to these materials and sometimes used independently as structural elements are numerous other nonmetallic materials. It is the purpose of this chapter to review briefly the more important of these latter materials.

ADHESIVES

by W. E. CASS * and A. F. ZAVIST †

14.1 INTRODUCTION

An *adhesive* ‡ is a substance capable of holding materials together by surface attachment. The bodies held together are called *adherends,* and the process of joining is called *bonding.*

Of the methods available for joining things together, adhesive bonding is among both the oldest and the newest. The knowledge of glues extends back to early history when the ancient Egyptians made wood inlays which are still in good condition. The development of modern synthetic resins has greatly increased the scope and utility of adhesives. Bonds between dissimilar surfaces, which were not practicable before, can now be readily made. As a result, design possibilities have markedly increased and adhesive bonding can often replace more expensive bolting, welding, or riveting operations.

The use of adhesives offers certain advantages over other types of bonding. Adhesives can be applied to a great variety of surfaces and combinations of surfaces. Normally, welding or solder-

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‡ Definitions of terms used follow those suggested by the American Society for Testing Materials, 1949.

ing is possible only with metallic surfaces, and riveting does not lend itself to brittle materials such as glass. By distributing stresses over the surface area, rather than concentrating them at points, adhesive bonding makes possible more efficiently designed structures. An example is the replacement of rivets by adhesives in the bonding of automobile brake linings. Adhesives can also be applied to mass-production methods fairly readily. Although the strengths of most adhesives are not high, they are adequate for many applications, and some of the newer synthetic resin materials are satisfactory for high-stress applications.

One disadvantage of adhesives is that bonding is not instantaneous. Sometimes an assembly must be clamped for an appreciable period of time until the adhesive has set. Another disadvantage is that resistance to high temperatures is limited, since most adhesives are organic materials. Generally, temperatures below 125–150 C are indicated, although some silicone adhesives can be used at 200 C or even higher. The bond strengths of both organic and silicone adhesives decrease appreciably in the temperature range 100–150 C.

For higher temperature applications (above 200 C) it is usually necessary to use inorganic adhesives and filling compounds, such as metallic silicates or phosphates.

Principles of Adhesion

14.2 COHESION AND ADHESION

A satisfactory adhesive must possess two properties: (a) it must *cohere* to itself and (b) it must *adhere* to the surfaces it is bonding. For example, water possesses very good adhesion toward wood; i.e., it wets wood readily and has a strong affinity for its surface. However, water has little cohesion (in the adhesive sense, at least) and is useless as an adhesive for wood. If the water is frozen, however, the strength of the bond is increased to such an extent (by increase in cohesion) that the wood will break before the bond does.

14.3 MECHANICAL VS. SPECIFIC ADHESION

Mechanical adhesion consists of the wedging and interlocking of the adhesive into crevices and around fibers of the adherends. According to modern thinking, mechanical adhesion is of only minor

importance, even with porous adherends.   Roughening of surfaces with sandpaper prior to bonding is effective probably because it gives clean, *active* surfaces rather than because it increases mechanical adhesion.   It is recognized, however, that surface roughness presents greater area for specific adhesion forces at the adhesive-adherend interface.

Specific adhesion depends upon three types of chemical-physical bonds (see Chapter 9): (*a*) polar bonds; (*b*) covalent bonds; and (*c*) van der Waals forces.

Polar and covalent bonds represent primary valence bonding. Polar (also called electrovalent, electrostatic, or ionic) bonds occur between ions.   Although the evidence is not clear-cut, this type of bonding may occur between an acidic adhesive and a metallic adherend, i.e., "salt formation."   Covalent (also called nonpolar) bonds are the type generally involved in organic chemical structures.   Electron pairs are shared between adjacent atoms in covalent bonding. Many organic bonds are believed actually to be intermediate between the two extreme bond types, i.e., possessing *both* covalent and polar character.   In adhesion, covalent bonding includes organic compound formation between adhesive and adherend, and chelate bonding.*   Hydrogen bonding † is sometimes included in this category. An example of hydrogen bonding in adhesion is the interaction of wood with an adhesive which contains groups (e.g., hydroxyl) which are capable of hydrogen bonding with the hydroxyl groups in cellulose.

Van der Waals forces (also called secondary or residual valence forces) include all bonding forces not strictly electrostatic or covalent in character.   Included are dipole-dipole interaction, induced dipole interaction, and dispersion forces.   They are of great importance in adhesion, particularly where nonpolar or chemically inert adherend surfaces are involved.‡

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* Chelate bonding (*chelation*) involves the formation of *ring* structures, either through hydrogen bonding or through the formation of cyclic "complexes" with metallic ions.

† Hydrogen bonding occurs when a hydrogen atom in a compound is attracted by two atoms instead of one.   The association of water molecules in the liquid state is the result of hydrogen bonding.   Strictly speaking, only one of the bonds to hydrogen is covalent; the hydrogen bond itself is better classified as an example of secondary valence forces.

‡ The importance of dispersion forces in the bonding of metals with nonpolar adhesives has been emphasized by Kraus and Manson.

14.4 TACK

The stickiness of an adhesive is called *tack*. This is a property of an adhesive still in the *liquid* state. Tack is a rheological phenomenon and is described by the tackiness equation,[*] Eq. 14.1,

$$Ft = \frac{3\eta a^2}{4}\left(\frac{1}{h_1{}^2} - \frac{1}{h_2{}^2}\right) \tag{14.1}$$

where F is the unit tensile stress applied to the joint, t the duration of its action, η the viscosity of the adhesive, a the radius of the (circular) joint, h_1 the initial thickness, and h_2 the thickness of the adhesive layer after time. t (Fig. 14.1). Important implications of the tackiness equation are:
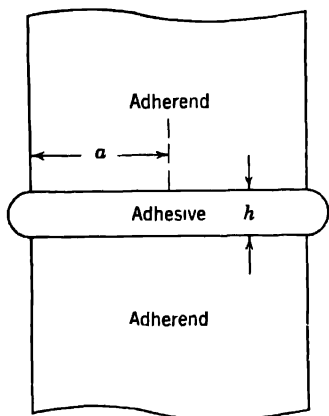
(a) There is no definite force opposing the breaking of the joint, i.e., the resistance to separation depends upon the rate.

(b) The product Ft is proportional to the viscosity of the adhesive

(c) The product Ft is inversely proportional to the square of the initial thickness of the adhesive layer.

(d) For any single value of t, the unit stress depends upon the area.

FIG. 14.1.

Adherend

a

Adhesive   h

Adherend

Tack is important because practically all adhesives go through a tacky stage and the initial strength (*wet strength*) of an adhesive assembly depends upon tack.[†] Certain adhesives, e.g., "pressure-sensitive" adhesives, remain permanently liquid in nature and depend solely on tack for adhesion.

14.5 SETTING OF ADHESIVES

Most adhesives do not remain permanently tacky but become converted to a hardened state. This process is called *setting*. An adhesive may set: (a) by solvent release (*drying*), or (b) by chemical condensation, polymerization, vulcanization, etc. (*curing*).

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[*] See J. J. Bikerman for a more complete discussion of the implications of the tackiness equation.

[†] At least one theory maintains that adhesion in general depends upon a "fluid, or quasifluid, or mobile state" at or near the adhesion-adhered interface (see S. Moses).

The release of volatiles in adhesives which set by drying is of considerable importance. Generally a predrying step before assembly is used, particularly with nonporous adherends. Careful control is necessary: if too much solvent remains, drying may be slowed down excessively; if too little solvent remains, an incomplete bond may result.

Adhesives that set by curing may or may not contain solvents. Where solvents are used, predrying again is of importance. Solventless adhesives (100 per cent reactive) have the advantage that no predrying is necessary. Curing is generally accomplished by heat. Catalysts, or "activators," frequently are added to increase the speed of curing. The *working life*, or *pot life*, is the period of time an adhesive, after mixing with activator or catalyst, remains suitable for use. *Shelf life*, or *storage life*, is the period of time a packaged adhesive can be stored under specified temperature conditions and remain suitable for use.

Some types of adhesives employ the process of "solvent activation." In this process the adhesive solution is applied to the adherend and the solvent allowed to dry completely. Just before assembly the dry surfaces are activated by treatment with a special solvent.

Another class of adhesives employs thermal fusion. Little or no solvent is used, and the process is analogous to the "welding" of thermoplastic resins.

14.6 CHARACTERISTICS OF SOLID ADHESIVES

In liquid adhesion, viscosity is the only inherent physical property contributing to bond strength (see tackiness equation). In solid adhesion, on the other hand, many properties of the adhesive are important: tensile strength, shear strength, impact strength, coefficient of expansion, etc. The failure of a solid adhesive probably does not involve the instantaneous failure of the total bond. Rather, it involves the propagation of a crack or flaw, analogous to the tearing of a sheet of paper. Possibly because of the lower probability of flaws, it is generally true that "the thinner the adhesive layer, the stronger the bond." * The usual tendency is to apply much more adhesive than is efficient. At the other extreme, too little adhesive may result in a discontinuous film, or "starved joint."

* An alternative explanation of the thickness-strength rule, involving the distribution of internal stresses, has been proposed by H. P. Meissner and G. H. Baldauf.

14.7   PREPARATION OF SURFACES

In order for an adhesive to function, it must *wet* the surface. Most surfaces are contaminated with foreign substances, including oxide layers. moisture, organic materials such as oils and greases, adsorbed gases, etc. Such contamination can interfere with the establishment of the bonds involved in specific adhesion. Therefore, surface preparation is of fundamental importance in adhesive practice. With many surfaces (e.g., wood, thermoset plastics, certain metals) the use of fine abrasives is advantageous. With other surfaces, solvent cleaning, vapor degreasing, or chemical treatment must be employed.

Sometimes a modification of the surface is necessary. An example of this is in the bonding of rubber to steel. The steel is first plated with brass. Vulcanization of rubber against the brass surface gives a strong bond, probably the result of the formation of copper sulfide primary valence bonds (from the copper in the brass and the sulfur in the rubber). Surface modification can be achieved also by the use of priming coats.

14.8   SELECTION OF ADHESIVES

Many factors must be considered in the selection of an adhesive for a particular job. In general, an adhesive should be compatible with the physical and chemical nature of the adherend surface. Thus, nonpolar adhesives are used with nonpolar adherends, such as hydro-carbon plastics and rubbers, and polar adhesives with polar surfaces, such as glass, ceramics, and certain metals.

The adhesive should also match the coefficient of expansion of the adherend. Where this is not possible or where adherends of widely different expansion coefficients are to be joined, a softer, more rubbery adhesive must be used. For example, unmodified phenolic resins are not satisfactory with metals. Even though high specific adhesion is probable, the hard phenolic resin cracks off under the stresses of dif-ferential thermal expansion. However, if rubbery materials are added, the resulting modified phenolic adhesives are useful bonding agents for metals. In general, one uses low modulus (soft) adhesives with high modulus (hard) adherends.

Sometimes the coefficient of expansion of an adhesive can be modi-fied to approach that of the adherend by the incorporation of suitable fillers. For example, if polystyrene (high coefficient) is used with brass (lower coefficient), small temperature variations cause the bond to crack. If aluminum oxide (lowest coefficient) is added in the

proper proportion to the polystyrene, cracking does not occur over a wide temperature range.

14.9 APPLICATION OF ADHESIVES

Liquid adhesives can be applied to adherend surfaces by brushing, spraying, roller coating, scraping, or extrusion. All these methods can be mechanized for high-production applications. After the adhesive has been applied and, if necessary, predried, the adherends are assembled. The assembly is then generally clamped or pressed, although this step may be omitted with adhesives showing high initial tack.

Dry adhesives can be applied in stick or powder form, using thermal fusion to liquefy the adhesive. In the plywood industry, adhesive film is used. This consists of paper impregnated and coated with a solid thermosetting resin.

Types of Adhesives

The following bases have been used in classifying adhesives: (*a*) chemical nature (protein, hydrocarbon, etc.); (*b*) raw-material source (animal, vegetable, synthetic); (*c*) nature of adherends (wood, plastics, metals, rubber); (*d*) setting characteristics (thermoplastic, thermosetting). Of these, the chemical classification is the most generally useful. However, an unequivocal classification is difficult because of the great diversity of materials involved and because many practical adhesives are mixtures. Below are listed broad classes of adhesives with brief descriptions of representative examples of each class.

14.10 GLUES

These are protein materials of natural origin. Glues are useful with fibrous materials such as wood, paper, leather, and fabrics. Examples are animal glues (from hide, bone, and blood) and fish glue. These show good strength, but have poor water and fungus resistance. Improved water resistance is obtained with casein glue (from milk), soybean protein, and zein (corn protein). However, none of these adhesives is completely water resistant and each may embrittle on aging

14.11 PASTES AND MUCILAGES

These adhesives are prepared from starches, dextrins, or gums (e.g., gum arabic) plus water. They spread easily and dry rapidly, but have little water resistance. They are generally used with paper. Li-

noleum paste is obtained from the sulfite waste liquors of paper making (contains lignin).

14.12 NATURAL RESIN ADHESIVES

Rosin, shellac, and asphalt are frequently used in adhesive formulations. All these materials lend themselves to hot-melt application. Asphalt emulsions are used as floor-tile cements. Shellac shows rather high specific adhesion to a variety of surfaces. However, the natural resins are now generally considered inferior to synthetic adhesives.

14.13 INORGANIC ADHESIVES

Sodium silicate is used in the manufacture of corrugated paper boxes. It is water and fungus resistant. Silicate cements compounded with inorganic fillers are useful for ceramic applications. Litharge-glycerine and magnesium oxychloride cements are used similarly.

14.14 RUBBER-BASED ADHESIVES

These materials, among the most versatile and widely used adhesives, are based on natural, reclaimed, or synthetic rubbers. They may be of the vulcanizing or nonvulcanizing type, and they can be applied from solution or emulsion.

Reclaimed rubber is the most common rubber-adhesive material. It shows good tack range, pot life, and aging properties. It has the further advantage of low cost.

Natural-rubber derivatives include cyclized rubber, chlorinated rubber, and rubber hydrochloride. Cyclized rubber forms a harder bond than other rubber adhesives. It was the basis for one of the earliest useful rubber-to-metal adhesives.

Synthetic rubbers include GR-S, butadiene-acrylonitrile copolymers, neoprene, butyl, and Thiokol. Nitrile rubbers and neoprene show excellent bonding characteristics and, along with Thiokol, are noted for oil and chemical resistance.

Polyisobutylenes are nonvulcanizing materials, ranging from viscous liquids to rubbery solids. Their chief use is in pressure-sensitive adhesives.

Rubber-phenolic adhesives consist of a rubber base incorporating a phenolic resin. They combine the specific adhesion and strength of phenolic resins with the flexibility and resilience of rubber. They are useful adhesives for bonding metals.

14.15 THERMOPLASTIC RESIN ADHESIVES

These resins generally remain soluble and fusible. They can be applied from solution or emulsion or by heat fusion.

(a) *Cellulose Derivatives.* Cellulose nitrate (pyroxylin) in ether-alcohol solution is known as collodion. Combined with other resins, cellulose nitrate forms the basis of common "household cements." These are conveniently used, but are highly flammable and have poor heat resistance.

Cellulose acetate has poorer adhesion and weathering properties than the nitrate, but better heat-aging properties. Cellulose acetate butyrate is similar to the acetate but has better moisture resistance and weathering properties.

Methyl cellulose, sodium carboxymethyl cellulose, and hydroxyethyl cellulose are water soluble and can be used as substitutes for natural gums.

(b) *Acrylics.* Methyl methacrylate (Lucite, Plexiglas) is used in solution for self-bonding. Ethyl acrylate is flexible and slightly tacky; it can be used as an ingredient in pressure sensitive tapes.

(c) *Vinyls.* The vinyls show great versatility in adhesive applications. They have quick tack and form tough, clear bonds to many adherends, both porous and nonporous.

Polyvinyl acetate is heat sealing and is widely used with cellophane and in food packaging. It forms a strong bond with glass and metals, as well as with porous adherends.

Polyvinyl butyral (Butvar) and polyvinyl formal (Formvar) bond well to a wide variety of materials. The chief use of the butyral is in the manufacture of safety glass.

Polyvinyl alcohol has outstanding resistance to oils and greases. It bonds well to paper, textiles, and leathers. Water-soluble and water-insoluble grades are available. All grades show water sensitivity.

14.16 THERMOSETTING ADHESIVES

During the curing process these materials are transformed into "three-dimensional," insoluble, infusible polymers. They possess limited tack initially, but form bonds which are strong, waterproof, mold resistant, and heat resistant. A disadvantage of the catalyzed types is short pot life (less than 1 hr in certain cases).

(a) *Phenol-Formaldehyde Resins.* These constitute the most widely used and most important class of thermosetting adhesives.

They form strong bonds and are used in the manufacture of waterproof plywood. Cures are usually made at elevated temperatures. Lower temperature cures require more acid catalyst, which may be harmful to the wood.

Rubber-phenolic adhesives have already been mentioned. Resin-phenolic adhesives are similar except that a thermoplastic resin, such as polyvinyl formal or polyvinyl butyral, is substituted for the rubber. A polyvinyl formal-phenolic adhesive, "Redux," has attained considerable success in England as a bonding agent in aircraft construction.

Resorcinol-formaldehyde resins are similar to phenolic resins. They are more expensive, but can be cured at room temperature.

(*b*) *Urea-Formaldehyde Resins.* These are light in color and generally cheaper than phenolic resins. Their resistance to moisture, chemicals, and high temperature is less than that of phenolic resins.

(*c*) *Melamine-formaldehyde Resins.* These are similar to urea resins, but have better water resistance.

(*d*) *Furane Resins.* These are acid-catalyzed resins, generally based on furfuryl alcohol. They cure to hard solids, exhibiting excellent adhesion and solvent resistance.

(*e*) *Polyurethanes.* These are reaction products of hydroxyl-containing compounds with di- or tri-isocyanates. They were developed in Germany during World War II. Polyurethanes can be used *per se* as adhesives for wood, plastics, and metals. Their chief use, however, is to increase the specific adhesion of rubbers, particularly to metallic surfaces.

(*f*) *Polyesters.* These are solutions of unsaturated alkyd resins in polymerizable monomers such as styrene or diallyl phthalate. They vary in properties from hard, brittle solids to rubbery gels. They have good water and solvent resistance, but lower heat resistance than phenolic resins. From the adhesive standpoint, their main use is in the production of glass cloth laminates.

(*g*) *Epoxides.* These resins, also called "ethoxylines," are the most recently developed class of thermosetting adhesives. They are poly-aryl-ethylene oxides and cure by condensation with amines, acid anhydrides, or other acids or bases. Epoxide resins cure without the evolution of volatile by-products and with little shrinkage. They show high bond strengths with glass, ceramics, and light metals.

(*h*) *Silicones.* Silicone adhesives are generally of the silicone rubber type and are used for bonding metals, ceramics, plastics, and silicone rubber itself. They have the broadest operating temperature

range in the field of organic adhesives: they do not embrittle at −50 C and they are reasonably stable at 250 C.

Carbon and Graphite

14.17   DESIGNATIONS

The element carbon occurs in widely varied forms, as described in Chapter 9. One form is the diamond, which is crystalline, transparent, and extremely hard. Another crystalline form is graphite in which the carbon atoms have a hexagonal, layerlike structure. A third form is amorphous carbon. In engineering, the name carbon is usually associated with the amorphous product. The two crystalline forms are referred to respectively as diamond and graphite.

14.18   SOURCE

Carbon, the amorphous product, is obtained by removing the volatile matter from lampblack, charcoal, petroleum, coke, or coal. The process involves baking at temperatures of 700 to 1200 C according to a slow schedule.

Graphite occurs in natural deposits particularly in Madagascar, Ceylon, and Mexico. The artificial variety may be made by heating carbon to a temperature of nearly 3000 C and holding for a sufficient time for formation of the orderly hexagonal crystal pattern. Some forms of carbon, for example that obtained from petroleum coke, are more suitable for graphitizing than charcoal or lampblack carbons. The latter cannot be graphitized to the same degree.

14.19   PRODUCTION PROCESSES

Most carbon and graphite parts for industrial use are formed by extrusion or compression molding. For carbon parts the petroleum coke, coal, and/or lampblack are mixed with pitch or tar and formed under pressure. The slow-baking schedule at 700 to 1200 C carbonizes the pitch or tar binder and removes the volatile matter. Graphite parts are made similarly, except that a graphitizable form of carbon is chosen and the final baking occurs according to a time-temperature cycle at nearly 3000 C to cause graphitization.

The carbon and graphite parts produced in this way are slightly permeable. They may be made impervious by impregnation with chemically resistant synthetic resins. The impregnated parts will retain fluids under pressure following this treatment, and their me-

chanical strength is improved. Suitable choice of the resin offers an impermeable material resistant to practically all chemicals that will not attack the carbon or graphite.

Parts of controlled porosity may be made by the techniques of powder metallurgy (see Chapter 16). The particles for porous parts are carefully sized. They are bonded by carbon in a sintering operation, forming a rigid and uniformly porous material. Commercial grades are available with average pore diameters from 0.0013–0.0075 in., which correspond respectively to 0.00047 and 0.0059 in. maximum particle size retained.

14.20 PROPERTIES

Carbon and graphite are chemically inert in practically all acids, alkalies, and organic compounds, with the exception of those that are highly oxidizing in behavior. In air, significant oxidation occurs at about 650 F for carbon and at about 750 F for graphite. Temperatures to about 6500 F are resisted in a reducing or nonoxidizing atmosphere. All forms of carbon volatilize without melting at atmospheric pressure and at a temperature of 6606–6687 F. The temperature resistance of impregnated parts is, of course, limited to that of the resin impregnant.

The thermal conductivity of carbon is high in comparison with other nonmetallic materials, and that of graphite exceeds values for some metals. Such high conductivity combined with low coefficient of thermal expansion gives carbon products very high resistance to thermal shock. Specific heat of carbon and graphite are approximately equal and change almost linearly from 0.15 at 0 C to 0.47 at 1000 C.

Although the electrical resistance of carbon products is high compared to metals, these products are still good conductors. This property is utilized in many electrical applications. Carbon products are not strong compared to metals and most plastics, but they have sufficient strength for many mechanical applications. Their elastic modulus is also less than that for metals and plastics. Typical values are listed in Table 14.1.

14.21 APPLICATIONS

Carbon products are available for structural applications as cylinders, squares, brick, tile, rods, pipe, and tubes. They are used for heat exchangers for pickling and plating solutions and other corrosive

Table 14.1 Typical Property Values for Carbon and Graphite Parts *

Material	Density, lb/cu ft	Strength, psi			Modulus of Elasticity, 10^6 psi	Electrical Resistance, ohm in. at 20 C	Thermal Conductivity, Btu/hr ft °F
		Tensile	Compression	Flexure			
Carbon	98	200–900	1700–9000	400–2600	0.75–1.9	0.0011–0.003	3–8.7
Graphite	96	440–900	1700–5000	800–2800	0.8–1.4	0.0003–0.0005	71–97
Impregnated carbon	120	1800	10,000	4400	2.8	0.0016	3
Impregnated graphite	127	2500	9,000	4700	2.2	0.0003	86
Fine porous carbon	69	190	850	600	..	0.007	..
Coarse porous carbon	69	80	300	160	..	0.008	..
Fine porous graphite	69	110	500	250	..	0.0012	..
Coarse porous graphite	69	50	270	140	..	0.002	..

* Values depend on source, size of part, and degree of calcination or graphitization.

liquids, for conveying pipes, for linings for valves, and as components and linings for absorption, fractionation, and distillation towers.

Carbon parts have many applications in the metallurgical fields where they are used as crucibles, furnace linings, trough linings, mold plugs, core shapes, and chill plates in brass, bronze, aluminum, iron, and steel foundries and mills. Graphite, being more expensive, is usually used for more specialized requirements. Examples are Jominy molds and riser rods in steel mills; fluxing tubes and thermocouple sheaths for aluminum; pit-ingot molds, mold-wash powders, and molds for centrifugally cast bushings in brass and bronze; sintering boats and die assemblies in powder metallurgy; for bearing seals; and for induction-heating crucibles and dies for continuous casting.

Natural graphite is also used for paint pigment, stove polish, foundry mold facings, pencil manufacture, packing seals, and as a lubricant. For lubrication applications, foreign grit must be carefully removed. The material may be used alone, mixed with oil. or in a colloidal suspension in oil. The latter is obtained by special deflocculation treatment of the graphite and is known as oildag.

Carbon and graphite are also used extensively in electrical applications where they serve as electrodes. Carbon is usually lower in cost for electrodes in production of abrasives, carbides, ferroalloys, and phosphorus. It is also selected for carbon arc-welding electrodes and for generator brushes. Both types have been used as electrodes for electric furnaces for production of iron and steel. Graphite is usually selected as anodes for electrochemical applications because of higher purity, higher electrical conductivity, greater ease of machining and assembly, and high oxidation resistance. The nascent oxygen in some electrochemical processes, especially those containing sulfates, nitrates, or concentrated carbonates, causes consumption of

graphite anodes at a rate depending on oxygen generation and its control. Little or no deterioration results in cathode applications.

Cement, Mortar, and Concrete

14.22 CEMENT

The Romans were probably the first to use cement. They found that a water mixture of pulverized volcanic ash would harden to a firm mass, even under water, and termed the material Puzzolan Cement. The next important development occurred in 1756 when Sweaton used lime, made from a limestone containing clay, for an underwater lighthouse mortar foundation. The two substances, clay and limestone, were first artificially mixed and calcined to form a hydraulic cement in 1824. This material was termed Portland cement because its structures had the same appearance as a limestone variety of English building stone known as Portland stone.

The proper mixture of clay and limestone for Portland cement is sometimes found in natural rocks. Such ore is calcined as it comes from the quarry and then is crushed and ground, forming a natural cement. This product is usable for applications having low strength requirements. Sometimes blast-furnace slag has the right combination of ingredients, so that it may be ground and used like Puzzolan cement. But most cement used today is a true Portland cement.

The mixture used for Portland cement has about 80 per cent carbonate of lime (such as limestone, chalk, or marl) and about 20 per cent clay (as clay, shale, or slag). The materials are ground, wet or dry, in a ball mill and then placed in round tunnel kilns. The kilns are slightly inclined and up to 250 ft long. They are slowly rotated so that the charge gradually tumbles from the entry at the high side to the exit at the low side. Heating is accomplished by gas or powdered coal burning at the center of the lower end of the kiln. During passage through the kiln the mixture of limestone and clay partly fuses and sinters together, forming a clinker. The clinker is often mixed with a small percentage of calcium sulfate after cooling. It is then ground to a fine powder. The chemical composition is not simple. It consists of at least two aluminates of calcium oxide, two silicates of calcium oxide, and lime (CaO).

When mixed with water and allowed to dry, Portland cement hardens, probably by the formation of hydrated lime which crystallizes and bonds the other materials together. First setting takes place within 24 hr. But hardening through the mass continues for as long

as 28 days, depending on the amount of calcium sulfate added to retard the process. High percentages of alumina replacing silica result in quick hardening in one or two days. Hardening may also be speeded to some extent by careful control of composition, calcining, and fine grinding of typical Portland compositions.

A high-alumina low-iron variety known as white cement is used for ornamental work because of its white color. Waterproofing varieties contain soaps, oils, or tannic acid added during the final grinding.

14.23 LIME

The variety of lime usually used in mortar, either with or without cement, is known as quicklime, or common lime. It is made by heating calcium carbonate in a vertical or a rotary horzontal kiln at high temperature. The temperature is usually 900 C or above so the equilibrium pressure of the released carbon dioxide is above atmospheric pressure. The commercial product consists almost entirely of calcium oxide, with small percentages of iron oxide, silica, and magnesium oxide.

When mixed with water, or slaked, heat is released, the volume and weight of material increase about 2 or 3 times, and a white powder, calcium hydroxide or slaked lime, is formed. If an excess of water is used, the material becomes puttylike. It will set and harden by drying of moisture, by crystallization of the hydrate, and by absorbing carbon dioxide or carbonic acid from the air, forming calcium carbonate. The process of hardening is slow.

Lime is available from suppliers in hydrated form. This form avoids the heat and reaction of slaking and gives a uniform product free of unslaked areas. Most lime used for mortar is of this type.

A magnesium variety is also available which contains magnesium oxide up to 40 per cent. It slakes slower than common lime, expands less, evolves less heat, and sets more rapidly.

Besides its uses in mortar, lime is also employed in marking athletic fields, as an acid neutralizer for soil, for the manufacture of paper, for the dehairing of hides prior to tanning, for the purification of illuminating gas, as a bleaching powder, and as a refractory or a chemical agent in metallurgical and chemical processes. The water suspension is used as whitewash.

14.24 MORTAR

Cement mortar is made by mixing cement and sand with water. The usual proportions are 1 part of cement to 2 or 3 parts of sand.

Enough water is added to mix the premixed cement and sand to a smooth working consistency.

The strength of cement mortar generally increases (1) with the proportion of cement used, (2) with the coarseness of clean sand used, and (3) with the density of the solid mass. Small additions of hydrated lime up to 10 per cent or increased amounts of Portland cement are used to improve workability and water tightness. Unslaked lime must never be added, since its expansion will disintegrate the mortar. The applications for cement mortar are for laying stonework, building blocks and brickwork, and for stucco exterior plastering.

Lime mortar is similarly made by mixing 1 part lime and 2 or 3 parts of clean sand with sufficient water. An alternative method is to mix the lime with water, forming a putty which is later mixed with sand when needed. With either method, the mortar or the putty should stand for a period of about 10 days for slaking to be complete. Even when hydrated lime is used, the mixture should stand from 1 to 3 days prior to use.

Lime mortars are not used for thick walls because of the slow rate at which they harden. Nor are they used in contact with wet soil or under water, as the hardening process requires loss of excess moisture or moisture released during conversion of lime to calcium carbonate by absorption of carbon dioxide. The principal application of lime is for interior plaster. Cattle hair or fiber is mixed with the mortar for base coats or scratch coats directly on wood, lath, plasterboard, or wire meshing. The hair is usually added to the lime putty, sand is then turned in, and additional water is added as the material is to be applied. Plasterboard and wire-meshing applications require less added hair than wood or lath applications. In the finer work the base coat for the latter is given a second coat, called brown coat, containing less hair. The finish or skim coat may be made from lime putty and white sand but more usually it consists of plaster of Paris or a mixture of 1 part lime putty and 1 or 2 parts plaster of Paris. The base coat is usually $\frac{1}{4}$ in. thick, second coats $\frac{3}{8}$ to $\frac{1}{2}$ in. thick, and finish coats $\frac{1}{8}$ to $\frac{1}{4}$ in. thick.

Plaster of Paris is prepared by carefully drying some of the water of combination from gypsum (calcium sulfate with 2 parts water of hydration to 1 part $CaSO_4$). Gypsum itself is used as a retarder for Portland cement, as a filler in paper and paints, and as blackboard chalk. It also is used to convert ammonia salts in soil to ammonium sulfate, thus holding nitrogen in the soil. By heating gypsum below

125 C, 1 part of water may be driven off to form plaster of Paris. When water is added to form a stiff paste, some of the plaster of Paris redissolves, forming gypsum crystals. The crystals precipitate out, leaving water free to dissolve more plaster of Paris, and the process continues in this manner until practically all the plaster of Paris has been converted to a hard mass of interlacing crystals of gypsum. Besides the use of the characteristic of plaster of Paris in plaster, it is also employed for plaster casts of statues, etc., for interior stucco, and for bandages for broken bones.

Cement and lime mortar is made by mixing cement with lime mortar. The lime mortar in the proportions of approximately 1 part hydrated lime to 5 parts sand is usually made 1 to 3 days before it is to be used. Cement is added just before using to make the proportions 1 cement, 1 lime, and 5 sand. This mortar is used for stonework above water and out of contact with wet soil, and for ordinary brickwork.

14.25 CONCRETE

Concrete is made by mixing cement with aggregates of hard, inert, stonelike particles. The aggregate may consist of coarse sand, broken stone, gravel, cinders or broken brick, or mixtures of these materials, depending on the application. Portland cement is used for most concrete today, particularly for concrete reinforced with soft iron bars or mesh, for concrete load-bearing members, and for underwater concrete. It may be mixed on the job by hand, or by continuous or batch process rotary mixers, or it may be premixed and brought to the job.

The strength of concrete depends on the mixture of materials used. Strength increases (1) with the proportion of cement, (2) with reduction in amount of water used, if enough water is added to provide thorough mixing, (3) with the size of the coarsest aggregate, and (4) with the proportions of fine and coarse aggregate of given sizes that result in the highest density. Sand in excess of the amount required to fill voids in the coarse aggregate reduces strength. Rounded stone in place of angular or crushed stone is also inferior in this respect.

Typical mixtures of concrete range from 1 part cement, 1½ sand, and 3 coarse stone aggregate (1:1½:3) through 1:2:4 and 1:2½:5 to 1:3:6. The first mixture is considered rich in cement and is used for highest strength requirements, as in columns, or for exceptional water requirements. The 1:2:4 mixture is standard for reinforced

floors, beams, columns, machine foundations, and for tanks, sewers, and other watertight work. The 1:2½:5 mixture is used for ordinary machine foundations, walls, piers, floors, abutments, sidewalks, heavy sewers, etc. The leanest mixture is used for unimportant heavy work in walls and foundations where stationary loads are involved.

Strength values range from 3000 lb/sq in. compressive strength after 28 days for rich medium-wet concrete to 1000 lb/sq in. for lean mixtures. Cinder aggregate gives low strength values, 800 to 400 lb/sq in., for similar mixtures. Strength increases over the 28-day value with aging by as much as 33⅓ per cent for medium-wet consistency and up to 50 per cent for wet consistency.

The transverse modulus of rupture of concrete is considerably less than the tensile strength, on the order of ⅓ to ⅙. The true tensile strength is approximately $\frac{1}{12}$ the compressive strength. Accordingly, concrete is seldom relied upon to support tensile stress. For example, beams, when required, are made with steel reinforcement.

Direct shear strength is 60 to 80 per cent of the compressive strength, but shear failure resulting from diagonal tensile loads may be only 5–10 per cent of the compressive strength.

Objects made from wet mixtures of concrete are completely waterproof if properly filled, and if the junctions are well wetted before covering with neat cement and adding the next section. Watertightness increases with cement content, age, thickness, and with aggregate size, provided the mixture is homogeneous.

Concrete resists external attack by mineral oils and, if hardened, by animal fats, vegetable oils, and dilute acids. Strong acids, electrolysis, and sea water tend to disintegrate it under certain conditions. Freezing retards setting and hardening and may cause a surface scale to crack from exposed surfaces placed in freezing weather. This can be avoided by artificial heating or by covering the surface with straw or other insulation.

Cork

14.26 PROPERTIES

Cork is a material that occurs in nature. It is the spongy outer bark of the cork oak tree, which grows principally in northern Africa, Spain, and Portugal.

It has a cellular structure, each cell surrounded by an impenetrable skin which encloses air. This structure accounts for the low specific

gravity of 0.15 to 0.20 when the outer hard bark is removed. It accounts for high resistance to the penetration of liquids, since capillarity is not effective in drawing liquids through it. And it also accounts for the low conductivity of cork.

The natural material is truly compressible. It will undergo compression with very little side flow as its Poisson's ratio is practically zero. Long subjection to pressure does not destroy the structure or its ability to return to original size when the load is removed.

The coefficient of fricton of natural cork is higher than that of most materials used for friction application (usually 0.5 dry, and 0.25 in oil). Presence of moisture and oil does not deteriorate the property. The principal limit is operating temperature. Cork will not bear sustained temperatures above 250 F, although it may withstand short surges to 300 or 350 F. Dry applications are therefore limited to light duty or heavy duty involving little slippage. Oil cooling and other means of heat dissipation limit the heat build-up on the cork and, since the friction coefficient does not deteriorate unduly in oil, the duty that can be carried may be increased.

Chemically, cork does not discolor or deterioriate in oil, grease, gasoline, and other petroleum products. Alkalies, some acids, and some organic solvents have a destructive action. Discoloration occurs with prolonged heating at 250 F or above as a result of slow distillation. Higher temperatures result in burning, but only in the presence of an external flame. Combustion produces a carbonized coating which inhibits further burning. Temperatures under 250 F, humidity, and atmospheric conditions do not cause aging.

14.27 APPLICATIONS

Cork is sometimes used in the form of blocks or slabs as trimmed from the natural material. In this form the material is quite variable, contains structural flaws, and is irregular in size, thickness, and shape. These limitations are often overcome by laminating the corkwood to produce greater uniformity and structural strength.

Compostions are also used to take advantage of the properties of cork and to alleviate its shortcomings for particular applications. Finely ground cork is combined with various binders to provide for expansion or contraction, and for fabrication into sheets, discs, tubes, blocks, rings, strip, balls, wheels, rods, and irregularly shaped articles. Laminations with cloth or vulcanized fiber improve tensile strength. Natural or synthetic rubber composites provide normal side flow under compression when that is required.

Typical applications are:

(1) *Stoppers, gaskets,* and *packings,* where compressibility, resilience, and resistance to many chemicals are employed for sealing metal, glass, and metal-glass combinations.

(2) *Thermal insulation,* particularly in cold-storage plants, trucks, and railway cars, either in block form or granulated for filling between walls.

(3) *Vibration insulation,* where compressibility and resilience are employed in cushions for machine tools, and where the unique surface is used for reducing reflection of air-borne noise.

(4) *Friction applications,* like clutches, wheels, feed rolls, fishing-rod grips, etc.

(5) *Floats* for life-jackets, gages, pumps, and carburetors which make use of the low specific gravity.

(6) *Floor coverings,* either cork tile, from the natural product, or linoleum, made from cork dust and various fillers with drying oils, and reinforced on the bottom side with burlap.

The newer synthetic plastics are replacing cork in many applications as technology reduces cost and offers additional design or service advantages to plastics. The applications of cork are important and valuable, however.

Felt

14.28 MANUFACTURE OF INDUSTRIAL FELT

The manufacture of felt follows the general operations of wool textile manufacture, except conventional spinning, weaving, or knitting are not involved. Wool fiber constitutes the basic material. It may be new fiber, reprocessed fiber, and/or reused wool. For some applications these classes of wool may be blended with other animal, synthetic, or vegetable fibers, particularly cotton. The fibers are blended and picked, carded, and then felted by a process known as hardening and fulling. The interlocking structure characteristic of felt is obtained in this operation through a combination of mechanical work, chemical action, moisture, and heat. Cross laying of carded fiber webs is usually employed to develop balanced strength. The rough surface of the wool fiber results in a nonraveling, porous, and resilient material.

Various finishing operations are employed, depending upon the application for the felt. Scouring and neutralizing follow the felting

operation and the material is then dyed and dried. The surface is sheared and sanded for lubrication and filtering uses; a rough or fuzzy surface is obtained for polishing uses; and an ironed or pressed surface is provided for smooth and compact finish. Chemical treatments may be applied to make the felt water repellent, to give it high wettability, to give stiffness for clean cutting or low distortion, and to proof the felt for resistance to mildew, fungi, flame, moth, and vermin.

Felt is available commercially according to standards of the S.A.E., the A.S.T.M., and the Felt Association. These specifications cover two forms, roll felt and sheet felt. Roll felt is usually made in lengths 15 to 30 yards long, 60 or 72 in. wide, and in thicknesses from $\frac{3}{64}$ to 1 in. Sheet felts are customarily made in 36-in. squares from $\frac{1}{8}$ to 3 in. thick. Roll-felt standards cover thickness tolerances, weight (usually lb/sq yd) tolerances, percentage of wool fiber, combined content soluble in water and carbon tetrachloride, ash content, tensile strength, and splitting resistance. It is made in soft, firm, extra firm, and back-check grades from almost 0 tensile strength to 500–600 psi. Sheet felts are made in extra soft, soft, medium, hard, and rock-hard grades to thickness and weight tolerances.

14.29 PROPERTIES

The properties of felt depend on the fiber blend, the construction, the density, and surface and chemical treatments, if any. In general, all felts have high formability because of their high elongation before rupture. They have high compressibility and resilience with less than 5 per cent permanent deformation after 30 per cent load deflection in compression. Their coefficient of static friction is approximately 0.20 with dry steel, 0.26 with glass, and 0.37 with clean wood. Their wear resistance varies directly with density and fiber quality, and inversely with applied load. Thermal conductivity ranges from 0.36 btu/hr sq ft F/in. for the heavier densities to 0.25 for the lighter densities. Combinations of wool with kapok fiber produce even lower conductivity and 0.80 sound-absorption coefficient above 512 cycles. Absorption for oil is exceptionally high, ranging from 160–180 per cent for the heavy densities to over 300 per cent for the lighter densities. Higher viscosity oils are absorbed somewhat better than low viscosity oils. Capillarity increases with density of the felt and in inverse proportion to oil viscosity. Temperatures from −60 F to 212 F do not affect felt in the absence of water. Prolonged exposure in water causes slight swelling, shrinkage in length, increased elongation, and a reduction in tensile rupture strength of 25 per cent. Water-repellent

treatments decrease these effects. Exposure to air, ozone, ultraviolet, oil, grease, organic solvents or weak inorganic acids has negligible effect. But strong acids, strong bases, or alkalies are injurious to strength.

14.30 APPLICATIONS

The unique properties of felt are utilized in numerous applications. The following list is typical of the more important uses.

(1) *Sealing.* High-density roll type is used for oil retention, intermediate density for grease shields, lower densities for household weather stripping, for dust shields on instrument cases, and automobile windows, and on confined oil or grease shields.

(2) *Wicking.* For moistening devices and bearing lubrication, high and intermediate density roll-type felt is used. Sheet types are used for ink-transfer rolls and rubber-stamp pads.

(3) *Filtering.* Low-density felt in the form of cloths or bags is used for clarifying of oils, paints, dopes, lacquers, enamels, and solvents, and as air filters for respirators and air-conditioning ducts.

(4) *Wiping and Polishing.* Sheet-type felt is used. The soft varieties are used for metal buffing wheels, medium grades are used for mirror and lens polishing laps, hard grades are used for glass tumbler, granite, and marble polishing laps, and the extra-hard grades are used for heaviest-duty polishing wheels.

(5) *Vibration and Shock Isolation.* Both sheet and roll types in all ranges of density are used for isolation, the denser types being chosen for devices to support heavier loads. Pads are used as stops, dampening supports for buffer blocks, and as padding in shipping cases.

(6) *Surface Protection.* Soft, roll-type felt is used for the underside of telephones, lamps, and similar articles to avoid damage to finished surfaces, and to provide nonskid support.

(7) *Thermal Insulation.* The lighter densities are used as linings for cabins, containers, and appliances to reduce heat losses or to control surface temperatures.

(8) *Sound Insulation.* Lighter-density types of roll felt are used to dampen instrument panels, dashboards, containers, and appliances, and to absorb air-borne noise above 500 cps.

Fiber

14.31 SOURCES OF FIBERS

The term "fiber" is applied to a filament or threadlike piece of any material. Sometimes a raw material that can be separated into threads is also known as a fiber. Under such a broad definition, fibers may be drawn from most any animal, vegetable, or mineral source.

Mineral Fibers. The mineral fibers of industrial importance are asbestos, glass fiber, slag wool, and metal wool. The latter is used mainly for filters and cleansing applications. Slag wool is used as thermal insulation, although glass fiber is of equal importance for this application. Other uses for glass fiber and asbestos are described in Chapters 9 and 10.

Animal Fibers. There are two principal types of animal fibers of commercial importance. One is animal hair obtained primarily from sheep, goats, camels, and pigs. Pig bristles are used in paint brushes. Many types of hair are used in upholstery and surface finishes. But sheep wool is the most important of the hair fibers. Its length varies from 1 to 8 in. and its diameter from 0.0018 to 0.004 in. It is graded by size and length, the "tops" being used for worsted yarns, and the "noils" for carded yarns. Both are used for fabrics having many personal and household applications. Wool waste for packing glands, etc., is made from carpet yarn with fibers not less than 3 in. long. Wool fibers are also employed for felt as discussed in the previous article.

The other source of animal fiber is silk produced by the mulberry silkworm or from the larvae of other moths. Silk from the mulberry silkworm is of high strength and elongation, and varieties from other moths are inferior in strength.

Vegetable Fibers. All vegetable fibers consist mainly of cellulose (see Chapter 9). They may be seed hairs, such as cotton, or the inner bark of plants (bast hairs), such as flax, hemp, jute, and ramie. Cotton and ramie fibers are white, flax fiber is a gray brown, and jute and hemp fibers are brown. Those with a high proportion of cellulose are flexible and elastic, whereas the woody types are stiff and brittle. Their strength varies considerably, but the relative strength in decreasing order usually is hemp, jute, manila, linen, cotton, and ramie. Products made from these fibers are discussed in the next paragraph.

14.32 PRODUCTS MADE FROM VEGETABLE FIBERS

Cotton is used for making batting, guncotton, cloth, and rope. The seed hairs or linters are separated from the seeds by ginning. The natural spiral-like twist of the fiber makes it especially suited to spinning of yarn. Very fine yarns are made from sea-island cotton grown on islands off the shore of the Carolinas. A variety known as mercerized cotton is obtaining by treating the fibers with strong caustic while it is under tension. The strength of the fiber is substantially increased by this treatment. The fiber also takes on a high luster and high absorption for dyestuffs.

Linen is the fiber obtained from the flax plant by a process called "retting," which involves steeping in water. The fiber consists of nearly pure cellulose and varies from pale yellow-white to gray. It may be bleached white with chloride of lime but some deterioration occurs. Linen fiber has luster, is stronger than cotton, conducts heat better, and absorbs about 6 to 8 per cent moisture from air, about the same amount as is absorbed by cotton. Linen does not withstand boiling in alkalies, bleaching powders, or oxidizing agents as well as cotton. It is used primarily for fine cloth.

Linen rags are the primary source of fiber for fine paper, but today most paper is made from wood pulp. The cheaper paper is made by using the portion of wood pulp which does not dissolve in water. Better grades are made by heating wood chips with solutions of acid calcium sulfite, sodium hydroxide, or sodium sulfide. These reagents dissolve the lignin of the wood and leave a nearly pure cellulose residue. The residue pulp is then bleached with chlorine, an insoluble filler such as clay or barium sulfate is added, and glue or a mixture of aluminum hydroxide and soap is applied as a size. The mass is run between rolls of the paper machine, forming a coherent sheet of cellulose fibers with interstices filled by the filler, and the surface coated with sizing.

Jute is obtained from the stalks of the jute plant by retting. The fiber obtained is 4 to 7 ft long and of a pale yellow-brown color. The short fibers are employed in paper making. Longer ones are used in the manufacture of coarse woven fabrics such as burlap, carpet bindings, as a substitute for hemp in twine and small ropes, as a filler in cable, and as an adulterant for other fibers. The chief defects are deterioration under dampness and disintegration of the fiber if bleached.

Hemp is the name applied to the fiber obtained by retting the hemp plant. Manila hemp from the *Musa textilis* is white, lustrous, light, very strong, and of great durability. It is used in the manufacture of highest-strength cordage. A variety known as sisal hemp is found in Central America, the West Indies, and Florida. It is light-yellowish in color, straight and smooth, and is used for paper making and for cordage, second only to manila hemp in strength. Other grades of hemp are dark brown and contain a mixture of cellulose and lignocellulose. They are more hygroscopic than cotton, less affected by moisture than jute, and are disintegrated by bleaching. They are used principally for twine and rope, and are little used for woven fabrics because of harshness and stiffness.

In making cordage, the fiber is first run into a continuous ribbon, which is then twisted or spun into a yarn. A strand is then formed by twisting a number of yarns together in a direction opposite to the twist of the yarn. A plain rope is "laid" by twisting a number of strands, 3, 4, or 6, together in the opposite direction of the twist of the strand. A cable or hawser rope is laid by twisting 3 plain-laid 3-strand ropes together in a direction opposite to the twist in the rope. The strength of the cable is less than that of the composite ropes, but greater elasticity and resistance to abrasion are obtained.

14.33 FIBERBOARD

Fiberboard is also called vulcanized fiber, hard fiber, and fiber. The base material is prepared by treating paper wood pulp or a textile fiber with a saturated solution of zinc chloride. This mass is consolidated under heavy pressure, and the soluble materials are then leached out by soaking in water. The fiber is then dried forming a hornlike material. A pliable variety may be prepared by treating with glycerine or glucose. The hard form may be sawed, drilled, and worked like wood. The soft forms may be molded. In general, vulcanized fiber parts have a specific gravity of 1.3, electrical strength of about 120 volts/mil thickness, a tensile strength of 5000 psi in thin or thick sections and about 8000 psi for $\frac{1}{4}$-in. thicknesses, and after seasoning they have enough flexibility to bend on a radius 10 times their thickness at room temperature, and 50 times their thickness after baking for 12 hr at 250 F. Vulcanized fiber is available in sheet and tube forms. Decorative textures or colors may be applied for some uses.

Leather

14.34   LEATHER MANUFACTURE AND APPLICATIONS

The term "leather" is used to designate the tanned and dehaired skin of an animal, and for articles made from a tanned animal hide. In industry the only leather of importance is that from steer hides. Best quality is obtained from the section back of the shoulders and close to the backbone. The size of this section is about 24 to 32 in. wide and 40 to 54 in. long.

Tanning is accomplished by treating the gelatine in a dehaired and cleaned hide to cause hardening. In this state the gelatine is not liable to decay. The treating process consists of steeping the hide in a water mixture of oak bark, tannin (tannic acid), chromic oxide, or certain other reagents from vegetable substances. Oak-tanned leather can be obtained $\frac{3}{16}$ in. thick with tensile strength of 3000 to 5000 psi, elongation (1 hr of loading) of 13.5 per cent, modulus of elasticity of 18,000 to 32,000 psi, proportional limit of 23,000 psi and density of about 0 035 lb/cu in. Chrome-tanned leather has higher tensile strength of 8500 to 13,000 psi.

The primary application for leather has been in belting. Single thickness of $\frac{3}{10}$ in. or cemented double thicknesses of $\frac{3}{8}$ in. are employed. Wide belting and long belting is made by cementing the necessary number of strips together. Belts are cleaned with a coarse cloth and are dressed with neat's-foot or castor oil during idle periods. The oak-tanned belting is not suitable where exposed to steam, dampness, or dripping machine oil. Rawhide and chrome-tanned belts are superior to oak-tanned for this service, and mineral-tanned belts and waterproofed belts are available for the worst service.

Rawhide is not a tanned leather. It is obtained by rubbing the raw hide with oils or fats, and then twisting and stretching the hide until the moisture is removed and the oil thoroughly impregnated. It is very strong, tough, and waterproof and is used mainly for belt lacings.

be used in applications subjected to steam, heat, or oil and grease. Metal mesh, wire, or sheet belting is also used. The trend to supplying motive power at each machine or tool has decreased the uses for belting, but it is still employed to operate auxiliary elements in many types of equipment and for conveyors.

Lubricants

14.35 TYPES OF LUBRICANTS

A lubricant is a material that is purposely placed between two machine elements that move intermittently or continuously with respect to each other, to reduce friction, temperature, and/or wear. Liquid lubricants are usually preferred where they may be retained. Plastic and solid lubricants are used where liquid lubricants cannot survive or remain.

Liquid Lubricants. Mineral oil is the most common lubricant of this type. It consists of a complex mixture of paraffin-, naphthalene-, aromatic-, and unsaturated-hydrocarbons which may be distinguished from crude oil by their lower viscosity. Redistillation, refining, and blending produce lubricating oils that range from spindle oils of low viscosity, hardly distinguishable from kerosene, to highly viscous, heat-resistant oils for airplane engines and steam cylinders. Compounding with animal and vegetable oils, or with fatty acids is employed to obtain properties for specific purposes. Small quantities of synthetic materials may be added to retard oxidation (antioxidant), to retard rusting (antirust), to provide wetting, to withstand localized high pressure (extra pressure additive), or to control foaming and emulsification.

Animal, vegetable, and fish oils were among the first used. Today they still have numerous uses alone or in compounding with mineral oils. Typical of these oils are neat's-foot, lard, and tallow oils of animal type; castor, polin, rapeseed, and peanut oils of vegetable type; and sperm oil of fish type.

Silicone oils of synthetic origin are growing in application. Their chief advantages are high temperature resistance to 350–375 F, a pour point of −100 F, and a very flat temperature-viscosity curve. Since their lubricating value differs from typical mineral oils, applications should be made in accordance with manufacturers' recommendations.

Water, air, and chemical liquids are employed as lubricants in some special applications. Water is used in ship-propeller bearings. Pressurized air is used for "floating" very high-speed centrifuge bearings. Chemical liquids often become lubricants when moving elements must be encased or submerged in processing such liquids.

Plastic Lubricants. Grease is the major lubricant of this type. Usually a grease is a suspension of metallic soaps in a lubricating liquid. Calcium and sodium soaps are most used and aluminum lead, and lithium soaps are used to a lesser extent. Synthetic resins and rubber may be added to some types to promote adhesive qualities. Available greases vary from nearly liquid to hard blocks, depending on the kind and quantity of soap used. They are usually selected for relatively slow-speed machine elements, especially open types operated intermittently. Another type application is for high-temperature components which would not retain liquid lubricants.

Solid Lubricants. Graphite is the most common of the solid lubricants (see earlier section of this chapter), either alone or mixed with oil or grease. Other types sometimes used are soapstone, talc, wax, disulfides of tungsten or molybdenum, and silver sulfate. All are usually limited to slow-speed service. The sulfur-bearing types are suited to extremely high pressure with steel or iron machine elements.

14.36 PROPERTIES OF LUBRICANTS

There are a great many factors involved in applying lubricants. The major ones are:

1. The nature of the relative motion involved.
2. The relative speed between members.
3. The nature of the load between bearing surfaces.
4. The magnitude of the load between bearing surfaces.
5. The temperature range under which the lubricant must operate.
6. The cooling required and method of cooling.
7. The method of supplying lubricant to the bearing surfaces.
8. The atmosphere in which the bearings will operate.
9. The bearing materials involved.
10. The design and finish of the bearing members.
11. The life required.
12. The friction losses allowed.

Each of these factors may impose limiting restrictions on the choice of lubricant. Selections should therefore be made with the aid of oil chemists or the supplier's representatives.

Viscosity. The most important property of liquid lubricants in thick-film lubrication is their viscosity. This property is defined as the ratio of shearing stress to the rate of shear, $\mu = f/(du/dh)$, where $f =$ the friction drag through the oil film divided by the oil film area, and $du =$ gradient or difference in velocity in an oil film thickness dh. The units of the viscosity coefficient, μ, are the *poise.* One poise equals one dyne sec/cm^2 in cgs units. Since the values are usually low, the *centipoise,* which equals 0.01 poise, is more frequently used. The centipoise equals 1.45×10^{-7} lb sec/in.^{2}, a unit called the *Reyn.*

Viscosities are usually measured industrially by the Saybolt universal viscosimeter. This instrument measures the time for 60 cc of oil at specified temperature to flow through a given orifice under its own weight. The Saybolt time in seconds cannot be used in design calculations but is converted into *kinematic viscosity* for this purpose by use of the equation KV, stokes $= 0.0022t - (1.80/t)$, where $t =$ Saybolt universal seconds. The units of kinematic viscosity are the *stoke.* The *centistoke* equals 0.01 stoke. The value of kinematic viscosity in stokes is multiplied by the density in cgs units to equal absolute viscosity coefficient, μ, in poises. Similarly, multiplying centistokes by density equals centipoises. The Saybolt viscosimeter is insensitive for low viscosity oils below 32 sec, and for such oils the Ostwald viscosimeter is used. It reads directly in kinematic viscosity.

Mineral oils decrease in viscosity with an increase in temperature at a rate of 0.6 to 6 per cent per °F. The A.S.T.M. has developed charts for predicting viscosities for temperatures intermediate of two measured values. The S.A.E. has developed a numeric system for expressing viscosity grades of lubricants. High pressures 5000 psi–15,000 psi) also cause a considerable increase in viscosity (125–1600 per cent).

Oiliness. Bearings designed for thick-film lubrication often, as on starting, operate with boundary lubrication. Other bearings often have boundary condition throughout their service. Oiliness is the property which may be of greatest importance under these conditions. In this sense, oiliness refers to a combination of wettability, surface tension, and slipperiness, all these qualities being required. There is no absolute method of measuring this property.

Specific Heat. Lubricants are often called upon to serve as a coolant while providing lubrication. The specific heat is therefore important in calculating heat balances. Values for petroleum hydrocarbons are approximately equal to

$$C = \frac{0.388 - 0.00045t}{S} \text{ Btu/lb°F}$$

where t = temperature, °F, and S = specific gravity at 60 F compared to water at the same temperature.

Specific Gravity. This property has no relation to lubricating value but is useful in changing kinematic viscosity to absolute viscosity. The specific gravity is usually referred to water, at 60 F for both. An American Petroleum Institute "Gravity," A.P.I., is also recognized. It is A.P.I. = 141.5/sp gr − 131.5. The temperature coefficient of expansion varies with specific gravity of oil from 6.5×10^{-4} for 0.70 sp gr to 3.5×10^{-4} for 1.0 sp gr.

Other Properties. Quite a few other properties of lubricants are determined primarily as specification tests to control product uniformity. They are oxidation resistance, thermal stability, acidity, saponification number (mg of potassium hydrate to saponify 1 g of oil), iodine number (per cent iodine absorbed, which indicates adulteration), lowest pour temperature, cloud point (temperature at which cloudiness occurs), flock point (temperature at which wax begins to precipitate), sedimentation, flash and fire points or temperatures, and emulsification. Unfortunately, these specifications cannot be used alone for the selection or substitution of lubricants. If one lubricant with given test values performs satisfactorily, a second may not prove equally satisfactory even though the test values are essentially the same. These tests are helpful in indicating properties and uniformity of product, but performance tests are also needed for selection purposes.

Wood

14.37 NATURE AND TYPES OF WOOD

Although the term *wood* is used to denote the fuel and to describe a small stand of growing trees, its industrial use refers collectively to the material or finished form of forest products. The words timber and lumber are also used. Timber describes large standing trees or large planks and beams cut from such trees.

Lumber is a more general term used for boards, planks, and other raw-material forms used in construction. Both timber and lumber are wood products.

Wood material consists of a skeleton of cellulose cells permeated by a mixture of other organic substances collectively known as "lignum." A small percentage of incombustible, inorganic (mineral) matter, or ash, is also present. Each year the new growth of trees forms new cells in the *sapwood*, the zone of wood next to the bark. The cells formed in the spring of the year are larger and have thinner walls than those grown in the summer and early fall. In the *coniferous* trees, that is the ones which retain their leaves at all seasons, the spring growth is usually lighter in color than that grown later. Some of the *deciduous* trees, that is the ones which shed their leaves each fall, have less spring growth and it is darker than occurs later. Because of the color differences in the cellular growth added during the growing season, each year's growth appears as an annular ring on the cross section of the tree.

Since only the outer sapwood rings participate in the growing process, the inner sapwood ultimately changes itself into a lifeless form known as *heartwood.* The heartwood is darker in color, stronger, and less subject to decay. It may constitute as much as 60 per cent of old trees but is, of course, less in young trees.

The wood derived from American trees is described as *softwood* or *hardwood.* This classification is not related to measured hardness but is according to the type of tree. Some of the so-called softwoods are actually harder than varieties of the hardwoods.

The softwoods are those obtained from coniferous trees, ones which retain their leaves. They grow in all the major forest areas, the northern, southern, pacific, Rocky mountain, and tropical forests. Typical softwoods are aspen, cedar, (red, white, Port Oxford), cypress, Douglas fir, balsam fir, white fir, hemlock, pine (eastern white, red, ponderosa, southern yellow, sugar, and western white), redwood, and spruce. Usually their annular growth forms parallel cells and straight grain which is easily split.

The hardwoods are the deciduous types which lose their leaves at the end of the growing season. Typical types are red alder, basswood, ash (eighteen varieties), beech, birch (twenty varieties), cottonwood (twelve varieties), elm (three varieties), gum, hickory, locust, maple (sugar, black, silver, red, bigleaf), oak (fifteen commercial varieties usually divided into red and white groups), yellow poplar, and black walnut. Both annular and radial, or ray, cells

are formed in hardwoods. This gives them a cross grain, and imparts high resistance to splitting. Fine-grain types have small, thin-walled cells and few vessels. Coarse-grained types have many vessels and large cells. The annular rings and the streaks of vessels in coarse-grained hardwoods impart desirable appearance, depending on the manner in which boards are cut from the logs.

A number of types of tropical wood are imported. Typical of these and the properties of chief interest are:

Balsa: lightest wood, 3 to 25 lb/cu ft.

Ebony: valued for its dark color, turning, and finishing.

Lignum vitae: one of the hardest, heaviest, and most durable woods.

Mahogany: easily workable, relatively little shrinkage. African variety (Khaya) and Philippine variety (Lauan) are also used.

Rosewood: valued for its finishing and rose odor.

Sandlewood: from India, valued for roselike odor.

Teak: high resistance to decay and low shrinkage.

14.38 PROPERTIES OF WOOD

Dryness. Moisture is present in green wood in three forms. It comprises over 90 per cent of the protoplasmic content of the living cells, it saturates the walls of the cells, and it fills the center of lifeless cells. Loss of this moisture causes twisting, checking, warping, and shrinking. The shrinkage is usually largest in a lateral or tangential direction and may amount to 7–20 per cent from green to oven-dry state. It causes checks or cracking longitudinally and reduces shearing resistance paralled to the grain. Although some checking and cracking result during drying, most wood is dried before it is used. Either air drying or kiln drying are employed.

In air drying, called seasoning, the boards are piled in an open shed and spacers are placed between layers to allow natural air circulation. This method of drying requires 1 month or more to dry 1-in. pieces to 10–20 per cent moisture by weight. It may take several years for larger pieces. Because of the relatively long time required for air drying, it is being replaced by kiln drying.

Boards are piled in a kiln in the kiln-drying method. Heated air is circulated at about 300 F, and moisture content may be reduced to 2 per cent by weight in a few days. Hardwood should be dried slower than softwoods. This method is generally employed for all hardwoods to be used for interior finish, patterns, and cabinet work, and for softwoods to be used for construction.

Dried wood is hygroscopic and will absorb moisture from the atmosphere up to the saturation point of the cell walls, usually 25–30 per cent moisture by weight. The reabsorption of water is accompanied by swelling, reduced strength and machinability, and the bonding strength with adhesives is impaired. Wood should be kept dry prior to working and painted or coated for protection afterwards when these characteristics are important.

Strength and Stiffness. The strength of wood increases in bending and compression with its density. Dense, fine-grained woods with at least six annular rings per in. and ⅓ of each ring of summer growth are therefore selected for heavy load-bearing members. Open-grain wood, which is light in density, is used for light framing, studs, etc.

Defects such as large, loose knots, excess sapwood checks, and decaying matter reduce strength, especially in the bottom, or tensile side, of beams. Wood with these defects should be limited to concrete forms, boarding and light framing. Tight knots which interrupt the grain on tensile members seriously reduce strength, compression is affected less (15 to 20 per cent), and elastic modulus very little.

Strength and stiffness are increased as moisture content is decreased. Advantage may be taken of the dry and seasoned strength on small components free from defects and for protected applications. It is customary, however, to assume the green strength and stiffness in applying large members for outside use, since checking may occur in such pieces and moisture may be reabsorbed in use.

The mechanical properties of green wood generally lie within the ranges shown in Table 14.2. Values for the many types of wood

Table 14.2 Typical Range of Properties, Green Wood

Property	Range of Values
Green moisture, %	40 to 120
Density, lb/cu ft	27 to 71
Elastic modulus, psi	800,000 to 2,000,000
Modulus of rupture, psi	5,000 to 14,000
Crushing strength, parallel to grain, psi	4,000 to 9,200
Compressive strength, perpendicular to grain, psi	370 to 2,100
Shear strength, parallel to grain, psi	600 to 2,400
Hardness, load to indent 0.44-in. ball ½ diam into side grain, lb	320 to 2,150

available may be obtained from United States Department of Agriculture Bulletins 479 and 556. The variation in strength between pieces of the same grade is high, ranging from ½ to 1½ times the average strength values.

Thermal Properties. The specific heat of practically all wood is about 0.327 when oven dry. The value increases, of course, with moisture content. The calorific value also depends on moisture content since the moisture must be vaporized by burning of the wood. Typical values range from 2700 btu/lb with 50 per cent moisture to 6300 btu/lb when kiln dry. Density also affects the calorific value, the more dense types of wood having higher values.

14.39 APPLICATIONS FOR WOOD

Perhaps the largest application for wood is its use in construction where it serves temporary uses as forms and scaffords, and permanent uses as interior finish, exterior finish, light framing, and heavy load-bearing members. Economy is the prime consideration in selection of type and grade of wood. The denser varieties of highest quality are required for heavy load-bearing members. But these grades are the most expensive, heaviest to handle, and hardest to cut. Less dense and lower grades are employed when possible.

Grading standards have been established by such groups as the National Lumber Manufacturing Association, Southern Pine Association, West Coast Lumberman's Association, and the Departments of Agriculture and Commerce. They specify classifications for lumber according to nature and extent of typical defects. Also specified by such groups are the standard sizes and the manner of cutting logs into boards. Municipal codes in some cities define permissible working stresses for classes of structures and grades of wood used.

Other large uses for wood are furniture, pattern making, and wood products such as toys, handles, etc. Many furniture and cabinet products employ veneers, which consist of a thin piece of expensive wood glued to a backing of cheaper wood. The expensive wood may be sawed into thin slices but this is wasteful because of the thicknesses required and sawdust formed. Slicing by moving the wood to a stationary cutting blade is more economical. Rotary cutting obtained by rotating the wood against the blade is most frequently employed. The wood is soaked in water or steamed before cutting. The thin sheets are held flat during drying, and are then glued to their backing.

Plywood is another popular form made by gluing three or more $\frac{1}{8}$-in. veneer layers together, the grain of each being placed at 90° to the adjacent ones. The material has good impact resistance and finds application in drawer bottoms, boxes, crates, paneling, flooring, etc.

Cooperage (barrels, kegs, tubs) was a large user of wood but is gradually being replaced by other types of containers. The slack type is used for dry contents, and the tight type for wet material. The latter must be made from high-grade wood with small pores, and is often coated with a film of wax.

Coatings or impregnants are used for protection. Dry wood is very stable at ordinary temperatures, but is attacked by bacteria and fungi under warm, moist conditions, as in contact with the ground. The purposes of preservation treatments are to prevent entry of moisture into the wood and to prevent fungi from feeding on the wood. Sapwood is more vulnerable in this respect than heartwood, but late cuts are more desirable than spring cuts.

Preservatives used are of two types. Creosote, a distillate or heavy oil of coal tar obtained from high-temperature carbonization of bituminous coal, is often used, either alone, or mixed with coal tar, petroleum, or wax. The latter materials are employed to seal the pores against moisture. Creosote coatings are often used on power poles, crossarms, and railway ties. A second type of coating is water-soluble metallic salts such as zinc chloride. This material is odorless, clean, and serves as a fire retardant, but is toxic. It can be painted but is subject to leaching in wet locations. Two new materials that are being used are zinc meta-arsenate [$Zn(AsO_2)_2$] and methylolurea. The former may be pressure impregnated at room temperature. The latter causes hardening and strengthening while protecting against deterioration. Methods used for applying creosote or zinc chloride are: (1) brush, mop, or spray; (2) dip in hot material; (3) steep in heated material; (4) pressure impregnate, which results in filling of wood cells; and (5) follow pressure impregnation with vacuum, which results in removal of free impregnant, leaving cell walls saturated.

Other uses for wood are crating, excelsior (basswood) for packaging, charcoal, and paper making.

Review Questions

1. What two properties must an adhesive possess? Upon what types of bonding does specific adhesion depend?

2. Describe the property called tack and indicate its importance in adhesive applications.

3. By what two mechanisms do adhesives set to a hardened state? What do the terms *pot life* and *shelf life* indicate?

4. In the selection of adhesives, what relationship is usually maintained between adherend and adhesive? Name five types of adhesives.

PART TWO

Processes

15 CASTING PROCESSES

15.1 INTRODUCTION

The casting process is the oldest, the most versatile, and the most flexible process for forming metals. Basically, it consists in introducing molten metal into a cavity or mold of the desired form and allowing the metal to solidify. There is practically no limit to the size, shape, and alloy of the castings that may be made. Castings regularly produced range from tiny dental inlays of rare metals to complicated steel castings exceeding 200 tons in weight. Almost any article may be cast with proper technique and a design which incorporates a full appreciation of the foundryman's problems. Numerous items could be mentioned that would be impossible to produce by any other method. Casting is not always the best solution to the production problem, but the possibilities of the casting method are of such significance that it should not be overlooked for either new or revised designs.

The type of molding material used has an important influence on the ease and cost of making the mold, the permanency of the mold, the speed of production, the rate of cooling of the molten metal, and the surface roughness, the dimensional tolerances, and the mechanical strength of the casting. It is convenient, therefore, in this chapter to divide the discussion between nonmetallic mold casting and metallic mold casting. In the former, sand mold casting will be considered first, and the discussion of other processes employing nonmetallic molds will follow.

Sand Mold Casting

15.2 MOLDING

Sand casting molds are made from bonded sand, and the correct mold form is obtained by using a wood or metal pattern of the desired part. The pattern for small or medium-size parts is placed in a flask,

a box-shaped container without top or bottom. Molding sand is rammed around it. For casting some metals a specially prepared layer of sand, called *facing* sand, is first sifted, or riddled, over the face of the pattern and then the flask is filled with regular sand, called *backing* sand. Patterns of simple design and with one or more flat surfaces may be made in one piece. Others may be split into two or more pieces to facilitate the molding operation, and for large intricate castings, a pattern may have dozens of parts.

Each part must be so placed that it can be removed, after the sand has been rammed around it, without disturbing the impression it has left in the sand. At least two-part flasks are needed so that the pattern may be removed. The portion of the mold in the lower flask is called the *drag*, and the upper portion is called the *cope*. Intermediate flasks known as *cheeks* are sometimes required for intricate pattern designs. A layer of *parting* sand is dusted over the mating surface of each rammed flask before ramming its mate so that the flasks may later be separated for removal of the pattern.

An opening extending from the mold exterior into the mold cavity is provided so that the molten metal can be poured in. Usually this opening is arranged so that the metal cannot impinge on the bottom of the mold. The opening is called the *sprue*, and the place it enters the cavity is called the *gate*. Fig. 15.1 illustrates the gate and sprue in an assembled mold for a gear blank, and the preparation of its drag and cope from a split pattern.

15.3 MOLDING EQUIPMENT

Molding operations may be classified as bench, floor, or pit molding. The main difference between them is the size and number of castings made and the equipment used.

Bench molding refers to the molding of small parts on a bench or table, each molder working alone. If the number of parts is small, all the operations may be done by hand. But if the foundry specializes in casting small parts, or if quantities are large, various types of molding machines may be employed. Machines are designed that will jolt the sand (for ramming purposes), squeeze the sand, turn over the flasks, vibrate the mold to facilitate the drawing operation, or draw the pattern. Some machines may perform a combination of these operations. The molder also uses a variety of small hand tools (slicks, trowels, etc.) for performing any sand "sculpture" that may be required.

Work too big for bench or machine molding is molded on what are usually termed the side floor and the main floor. The work molded on the side floor can ordinarily be handled by two or three men without the use of mechanical handling equipment. Main-floor molding requires the use of some type of lifting crane. The molding procedure is fundamentally the same as for the small bench work.
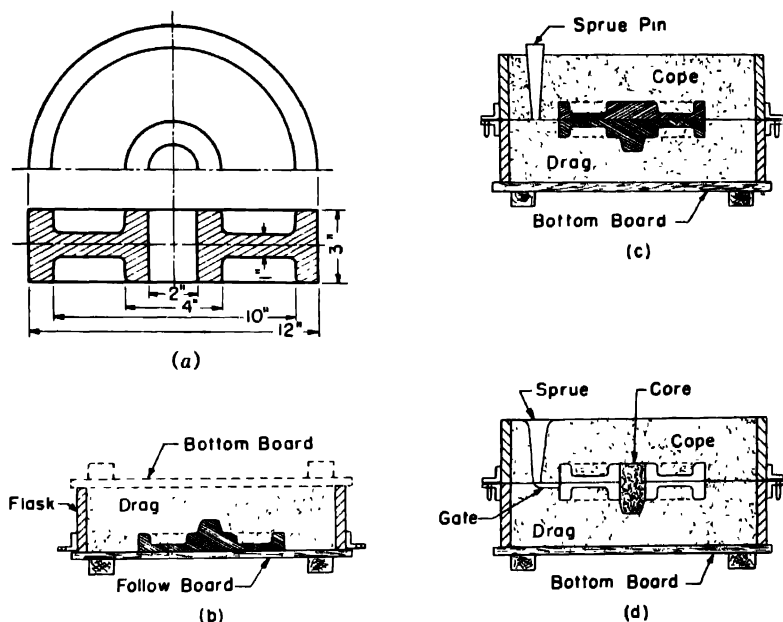
FIG. 15.1   Mold for a gear blank. (a) The machined blank. (b) The drag. (c) The cope. (d) The finished mold.

Some parts require a drag too large to roll over when filled with rammed sand. For them, the drag portion is made in a hole or pit dug in the floor. A drag pattern is "bedded in" on regular molding sand. If there is a hollow space inside of the drag pattern, the sand is rammed through openings in the pattern, either by building part of the pattern as ribs or by making it in sections which can be joined together as ramming proceeds. When the ramming of the drag is completed, the cope part of the flask is put on and rammed, then lifted off and placed on stools or standards and hand finished. Sometimes it is more convenient to ram up a relatively simple basic pattern in the floor pit and to obtain complicated details by placing large dry-sand sections (cores) containing the final contours around

the walls of the basic pattern impression. When much very large work is to be done, a concrete-lined pit is provided. Such a pit withstands the high fluid metal pressure better than a hole in the floor sand alone. Moreover, it keeps out moisture, facilitates the setting of cores, and provides a suitable anchorage for tie bars used to hold the top of the mold down so it can resist the pressure of the molten metal.

All foundries do not use the same types of molding equipment. Choice depends on plant layout and the types of castings regularly produced. Sand conveyors, automatic sand sifters, pneumatic rammers, and sand-slinger ramming units are examples of power-driven equipment used in some floor and pit molding foundries Because of the variety of equipment in use, it is to be expected that a mass-production foundry and a smaller one engaged in job-shop work might mold the same job in somewhat different fashion. Pattern alterations might, therefore, be required for work sent from one foundry to another in order to adapt the pattern to the molding methods in use. This point has not been generally appreciated in the past, and has resulted in some misunderstanding concerning the ability of foundries to cast certain jobs.

15.4 TYPES OF MOLDS

The two types of sand most commonly used by the foundryman are referred to as *dry sand* and *green sand*. Both contain bonding agents such as fire clay, bentonite, and cereal or liquid binders, and a controlled amount of moisture to promote cohesion. The dry-sand mold is dried thoroughly by baking at 200 to 600 F before it is closed and poured. The green-sand mold is closed and poured without any preliminary drying operation. The type and quantity of sand grain and binder depend on which procedure is to be used. Binders are chosen for ability to burn out at molten-metal temperatures so that molds and cores will collapse under compression and allow normal shrinkage to occur without damage to the casting.

Green-sand molds have been found essential to the commercial manufacture of castings of intricate design because the green sand does not exert as much resistance to the normal contraction of the casting as does dry sand. This reduces the strains that must be supported by the solidifying metal, and thereby reduces the formation of hot tears or cracks.

Dry-sand molds have a firm mold face which is better able to withstand the metal weight and pouring erosion; and since their mois-

ture content is to be removed anyway, they do not have to be molded and poured the same day. The dry-sand molds also require less care in molding, but they shrink a little in drying and are thus likely to be less true to form and size.

A modification of the green-sand molding procedure is known as *skin drying*. In this procedure the face of the mold is either riddled to a depth of ½ in. with a drying type sand or the green-sand face is sprayed with a special binding material. Drying is accomplished by rapid heating with a gas torch or by a short air-drying period. This gives a firm mold face, as in a dry-sand mold, with the more collapsible body of the green-sand mold. Such molds have proved of great advantage in making some medium-sized steel castings of intricate design.

Loam is occasionally used as a molding material in pit molding operations. A built-up section is first prepared of brick and iron parts. This is then plastered with a loam mortar which is shaped by sweeps or skeleton patterns. The loam is dried thoroughly before pouring.

Cores are used in molds to obtain holes, internal cavities, undercuts, etc., that are not molded with the external contour of the pattern. When the cored cavity engages the external contour and has a diameter or width greater than its length, the core can frequently be molded by the pattern itself. This type is known as a green-sand core, and it is made from the same sand and in the same operation as the mold. Dry sand cores are used for more complicated sections. They are made in separate forms, called *core boxes,* are dried by oven baking, and are placed in the mold before it is closed   Dry-sand cores are used with both green- and dry-sand molds:

15.5 TYPES OF PATTERNS

The types of patterns used may be classified as (*a*) single loose patterns, (*b*) gated patterns, (*c*) match-plate patterns, (*d*) cope and drag patterns, and (*e*) special pattern equipment.

Single Loose Patterns. This is the simplest type of pattern, and it is used only for very limited production or for very large castings. The pattern may be split to facilitate molding, but it contains no gates, sprues, or risers (reservoirs for surplus molten metal), and the cope and drag must be made together since the pattern is not located with respect to the flask. The time required by the molder to cut gates and risers by hand increases the cost of producing castings from

these patterns, and may cause a variation in the quality of the castings. For these reasons small castings in even moderate quantities are often produced from other patterns.

Gated Patterns. Some time is saved in the foundry by having the gates formed by pieces attached to the pattern. The location and size of these gates should be left to the judgment of the foundry. Single-gated patterns are used for comparatively small quantity production.

Match-Plate Patterns. Rapid production is facilitated by mounting the drag half of a split pattern on one side of a wood or metal plate and the cope half directly opposite on the reverse side. This plate is attached to the drag flask and used like a follow board when ramming the drag; the cope sand is rammed against the reverse side. Finally the match-plate pattern is removed, leaving a cope and drag that match perfectly at the parting line. The gates are generally made by the pattern at the same time.

The match plate itself need not be flat so long as it is of uniform thickness in the direction normal to the parting of the mold. This feature permits patterns with an irregular parting line (e.g., hand-wheels and propellers) to be handled with comparative ease.

Although the match-plate pattern has a high first cost, this is more than compensated by the reduced labor cost per piece in large quantity production.

Cope and Drag Patterns. Separate cope and drag patterns facilitate rapid production on medium to large castings because one molder or group of molders may ram up the cope while another molder or group works on the drag.

Special Pattern Equipment. Special patterns may be used for some castings where the quantity to be made is low and further orders are not expected. Two of these are sweep patterns and skeleton patterns. Sweep patterns are made to the cross section of the mold, and the mold is made by sweeping them through the length of the desired part. Skeleton patterns are made of the most inexpensive construction, usually of open type, which will permit the molder to make the mold. He may use clay to fill in spaces on the pattern and give it a continuous face. Patterns of this type should be considered only after consultation with both the patternmaker and the foundryman. Their use always increases the foundry cost but this may be offset by the saving in pattern cost.

15.6 WOOD VS. METAL PATTERNS

Various factors to be considered in determining whether a pattern is to be made of wood or metal are cost, size, durability, production, and obsolescence.

Cost. Wood, being cheaper, is most used.

Size. Beyond a certain size, all patterns are made of wood.

Durability. Wood patterns are easily warped by moisture and in handling may become roughened, torn, and even broken. Sometimes wooden patterns are metal lined in places subject to most wear and tear.

Production. If the size is not too large, high productivity jobs should always be made of metal.

Obsolescence. Where pattern changes due to redesign are likely to occur, the patterns should be made of wood.

The patternmaker should choose the type of pattern and its construction. When the foundryman and the patternmaker are not in the same organization, it would be well to consult the foundryman on the methods of molding and the pattern construction which will best suit the job. Frequently, changes in construction which may even increase the pattern cost will make possible significant savings in the foundry. Thus, a higher cost pattern causing somewhat decreased foundry costs may actually provide the least over-all cost of the finished casting.

15.7 PATTERN DESIGN

Although it is sometimes necessary for the designer to design the patterns for a casting, it is more frequently the responsibility of the patternmaker to make the pattern from which the part can be cast "to the drawing." Some of the points relating to the design of patterns which have an influence on the design of the casting are mentioned below.

Parting Lines. Since the flasks used to make each section of the mold are most conveniently parted in one plane, the parting line on the pattern should be on the same plane, if the casting can be so designed. This makes for economical pattern and molding costs with all types of pattern equipment; although where production matchplate equipment is used, adherence to this rule need not be quite so rigid. Fig. 15.2 illustrates two parts redesigned to facilitate parting.

Locating Points. When the finished casting is to be laid out for machining operations, it is advisable to facilitate checking in the pat-

tern shop, foundry, or machine shop by indicating on the drawing the position on the pattern for locating reference points. Such points should be located so they will not be influenced by core shift or shift of the cope or the drag. That is, they should be placed on the pattern, on the same side of the parting line, and as far apart as the size of the casting will permit. Surfaces which have no finish allowances and are held to close tolerances usually serve this purpose very well.
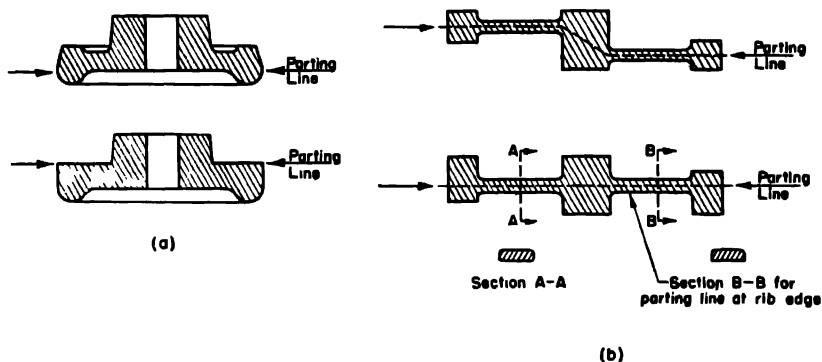
Fig. 15.2. Redesigns which facilitate parting. (*a*) Lower design eliminates need for overhanging sand in cope. (*b*) Lower design of four-spoke crank gives straight parting line either at centerline of the arm (for section *AA*) or at the bottom of the arm (for section *BB*).

It is also helpful on some castings to include lugs, bosses, or other surfaces for locating and supporting the part during the machining operations. Sometimes such jig aids will serve no other purpose and, if undesirable on the finished part, may be removed after machining is completed.

Core Prints. Core prints are sections put on the pattern to provide adequate location and anchorage of dry-sand cores. The length of the core print should generally equal the core diameter or width, but for prints that must balance overhanging cores, or overhanging sections of drop cores, a much larger print may be required.

Pattern Allowances. The dimensions on the pattern differ from those on the drawing to allow for metal shrinkage, distortion, core shift, draft, and machine finish. Such allowances are made by the patternmaker and serve the following purposes.

Shrinkage allowances provide for the contraction in dimensions of the solidified casting as it cools from its freezing temperature to room temperature. This shrinkage ranges from $\frac{1}{32}$ to about

⅝ in. per ft, depending on the metal; and it is added to the pattern so the finished casting will be of the correct size. The design of the casting, the restraint offered by projecting sections, and the resistance of the mold to the contraction all limit the shrinkage which will occur in different sections, and thus complicate the patternmaker's problem of allowing for proper shrinkage.

In some designs, it is necessary to add an allowance for distortion and core shift. A casting of "U" section, for example, should have the open ends converged enough that the shrinkage of the closed end will straighten the side members of the finished casting. The initial convergence is the distortion allowance. An example of a core-shift allowance is the metal (called *backing*) added to a thin section to assure necessary thickness, in accordance with the expected tolerances on core placement.

All surfaces perpendicular to the parting plane are given a slight taper, or *draft*, to permit easy removal of the pattern without excessive loosening (makes mold larger), or tearing of the mold walls. The amount of draft usually allowed depends on the shape and size of the castings, the molding method, and the type of sand used. The amount of draft is generally not less than ⅟₁₆ in. per ft. This may be added to or subtracted from the drawing dimensions, according to its effect on the subsequent use of the casting. When no instructions are given, the patternmaker will ordinarily divide the draft, i.e., add one-half at the parting line and subtract one-half away from it, if the wall thickness permits.

Metal is also allowed for "cleaning-up" surfaces to be finished by machining. This allowance must be sufficient for the machinist to take a cut which removes normal surface indentations and gets below the surface scale as well as the hard metal directly beneath. The location of the machined surface in the mold (drag is preferred—add extra for surfaces in cope), the metal, and the machining setup to be used also affect the amount.

Pattern Identification. For convenience in using patterns in the foundry, all wooden patterns and core boxes are painted in accordance with a standard practice.* Finished surfaces, unfinished surfaces, seats for loose pattern pieces, core prints, and stop-offs are all designated with a distinctive color or colors.

* The reader is referred to United States Dept. of Commerce Commercial Standard DS-19-30 or American Recommended Practice B45.1-1932 of the Procedure of the American Standards Association for a discussion of this practice.

15.8 DESIGN OF CASTINGS

The ideal casting from the standpoint of the foundry would be of such shape that (a) all its parts could be molded and poured easily, (b) it could be fed from one riser at the highest point in the mold, and (c) the solidification would proceed regularly from the lowest point to the feeding head, as in an inverted cone. Seldom can the designer achieve this ideal because of the limits placed on the shape by the functions of the casting. But an understanding of the mechanism of solidification and the effects caused by faulty design should permit the designer to introduce modifications which enable the foundryman to handle any remaining difficulties by reasonable foundry procedure—thus producing sound economical castings to the advantage of both groups.

The three main characteristics of solidifying metal which affect the soundness of a casting are the melting temperature, the volumetric contraction or shrinkage, and the strength in the temperature zone just below freezing. The higher the melting temperature, the higher the temperature at which the metal must be poured, and the greater the rate of cooling in the mold. The high rate of cooling makes it difficult to pour thin sections without having them freeze before they are completely filled. Increased handling difficulties may also result when the pouring temperature is high. Large shrinkage makes it necessary to use large risers (also called headers or feeders) which will freeze later than the casting and will supply liquid metal to compensate for the loss in volume as the solid metal cools. The strength of the metal at a temperature just below freezing is important, because the cores and the mold may offer considerable resistance to the contraction, and the internal strain which occurs shortly after freezing may cause a fracture if the strength is low.

Of the commercial metals cast in sand, steel probably offers the greatest difficulty. It has a high melting point, a high volumetric shrinkage, and, in common with other metals, a low strength at temperatures near the freezing point. The technique for casting steel has therefore been more exacting, in general, than for other metals, so it is particularly important that steel castings be properly designed. The design precepts which have been found expedient in designing steel castings are reviewed below. The same principles will, in general, apply also to casting of other metals, although the degree of importance may differ. A properly designed pattern

for a steel casting may therefore not prove suitable for casting other metals without changing the gates, risers, and dimensions, and vice versa.

15.9 DEFECTS IN CASTINGS

Sand castings are subject to certain defects which, in a well-designed casting, are controllable by proper foundry technique, but are not wholly predictable or preventable. Most defects are hidden below the surface of the casting and so cannot be detected by visual inspection. The designer must therefore either design to avoid or minimize such defects, or accept certain shortcomings and make allowances for them. The defects associated with the foundry practice include internal blowholes, slag inclusions, and centerline weakness (the junction of grains grown from opposite mold faces). The defects more directly attributable to poor design are *hot tears* and *shrinkage cavities*.

15.10 HOT TEARS

The cause of hot tears is excessive internal stress on the metal when its temperature is slightly below the freezing point. This stress may be caused by large temperature gradients in the casting, by a design which opposes contraction, or by stresses set up through the resistance of the mold to contraction.

Hot tears can be prevented by (1) eliminating sections which remain hot after others have cooled considerably and (2) by eliminating the stresses, particularly the concentrated stresses.

Hot sections, or hot spots as they are sometimes called, may be formed by a difference in section thickness. The thinner section freezes first and is contracting even before the heavier section has solidified. The heavy section thus becomes a hot section. Occurrence of hot sections of this type can be reduced to a minimum by *designing all sections of a casting with uniform thickness*.

Even with uniform thicknesses, hot spots will still be formed at the junction of two or more sections because the ratio of cooling surface area to metal volume is less than for the straight sections. These junctions therefore cause a thermal gradient and accompanying stress. Since they also provide conditions for stress concentration, they are quite favorable to the formation of hot tears. The stress concentration can be reduced by *using a fillet at sharp corners or junctions and by making all changes in sections as gradual as possible.*

In some intricate castings it is not possible to avoid hot spots and thermal gradients. With these designs the foundryman may
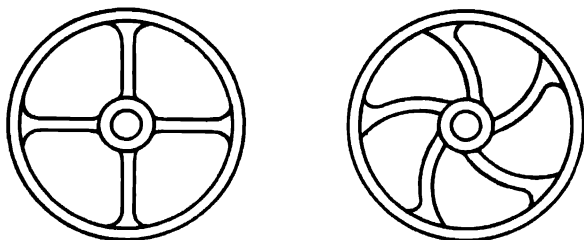
FIG. 15.3. Design of a large wheel with curved (right) instead of straight (left) spokes to allow the rim to contract without introducing excessive internal stresses.

reduce the stresses by use of mold relieving technique. But it is frequently possible for the designer to produce a better job by *designing the casting in two or three parts*, which are later assembled by welding or bolting.
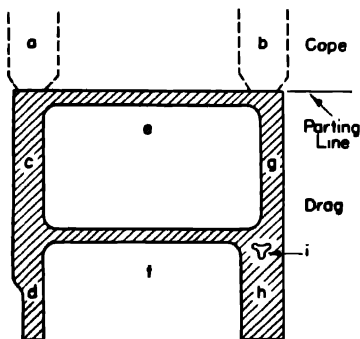
FIG. 15.4. Cross section of casting showing the formation of a shrinkage cavity. Sections e and f, being thin, solidify quickly and are easily fed by the headers on each side. The heavy section, h, being below the lighter section, g, and separated by g from the riser, cannot be fed effectively, and consequently shrinkage cavity i is produced. Design of these sections as at c and d would eliminate this effect.

Another way of reducing these major stresses in an enclosed cast structure is to use members that are slightly curved or waved. Connecting members are usually chosen for this purpose, and they are distorted as the heavier sections cool, thus *reducing the internal stresses* without tearing. Fig. 15.3 is an example of a design that incorporates this principle.

15.11   CONTRACTION_CAVITIES OR SHRINKAGE CAVITIES

These cavities are caused by lack of sufficient metal to care for metal contraction at the time the casting solidifies. They are found in sections that must be fed through smaller sections, as illustrated in Fig. 15.4.

Such cavities are objectionable because they reduce the static strength of the section, they increase the possibility of casting leaks under

pressure, and they promote the fatigue failure of castings subject to vibration. Although these cavities could be avoided by using a riser to feed molten metal to every hot spot, it is not always convenient for the foundryman to go to the expense of such a procedure. The foundryman may also mold the casting in a different manner than the designer anticipated, thus making some hot spots inaccessible. It is therefore much sounder practice to design the casting with the supposition that none of the junctions can be fed from outside reservoirs.

Briggs, Gezelius, and Donaldson [*] have made a study of various junctions in steel castings. Five basic sections, L, T, V, X, and Y, with fillets and cores of various sizes, were poured without a riser so that the junction had to be fed from the arms. The results of these studies are summarized in Fig. 15.5, which shows the best design studied, and an alternate which is considered satisfactory. In the L and V shapes, the junctions having radii that make the corner slightly narrower than the arms seemed most satisfactory. In the X section, it was found that a considerable offset of the arms gave the smallest shrink cavity. For T and X sections, the radius at the sharp corners should not be large. Best re-

FIG. 15.5. Designs of junctions that minimize formation of shrinkage cavities and cooling stresses. The sections at the left are considered best and most practical, those on the right are satisfactory. Where sections several inches thick are joined, the cores shown are used at the juncture to equalize effective section thickness. (*From Steel Castings Handbook, Steel Founders Soc. Am., 1941; originally from C. W. Briggs, R. A. Gezelius, and A. D. Donaldson, Steel Casting Design for the Engineer and Foundryman, Preprint 38-28 A.F.A.*)

results in T, Y, and X are obtained in sections several inches thick by using a central core.

* Steel Casting Design for the Engineer and the Foundryman, by C. W. Briggs, R. A. Gezelius, and A. R. Donaldson, *J. Am. Soc. Naval Engrs.*, May 1938; also *Trans. Am. Foundrymen's Assoc.*, Vol. XLVI, 1938, p. 605.

15.12   DIRECTIONAL SOLIDIFICATION

The term "directional solidification" refers to the solidification which proceeds *along* a cast member in the direction of the hotter metal.   Solidification of this type differs from progressive solidification, which is the freezing of the metal from the mold-metal interface toward the center of the cavity.   By controlling the direc-
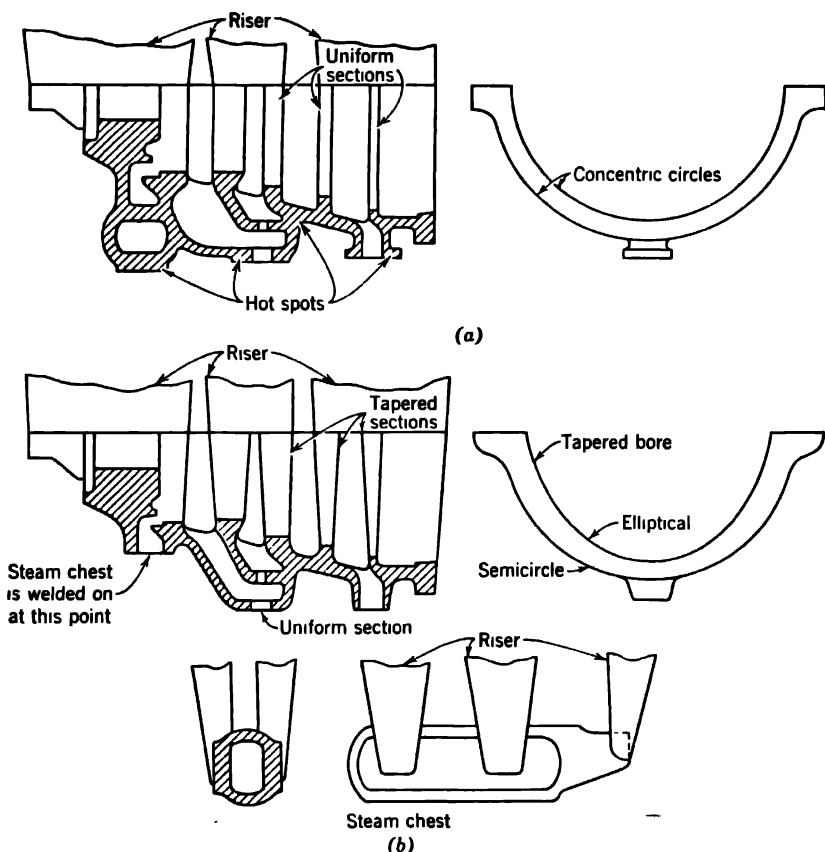
Fɪɢ. 15.6.   (a) Original design of casting.   (b) Casting after redesign.   Note use of tapered cross section to control directional solidification.   Extra padding could be removed by machining if uniform wall were required.

tion of solidification so that the casting freezes toward liquid metal feed heads which can supply voids caused by shrinkage, production of sound castings is aided considerably.   Such solidification can be accomplished by the proper placement of feeding heads, by using

tapered sections (narrowest section most remote from feeder), and by proper use of chills.

Chills are metal sections inserted in the mold to remove an extra amount of heat from the molten metal. External chills remain in the sand and do not become a part of the casting. Since internal chills are rarely melted by the molten metal they usually retain their form, although they are a part of the casting. Their use is discouraged, because porosity or other internal weakness is often caused by them, especially when extreme care is not used regarding their cleanliness.

The use of tapered sections to control the direction of solidification is illustrated in Fig. 15.6. This method seems a direct contradiction of the recommendation that uniform sections be employed. Actually, the designer cannot be sure of the method of molding and may apply a taper in the reversed direction. If he provides a uniform section, however, the foundryman can usually obtain the correct solidification. In castings where every advantage must be taken of the principle of directional solidification, the designer and the foundryman should study the problem together. Frequently, the use of a small model will facilitate the discussion and will help to visualize both the original design and any changes that may be suggested.

15.13   EFFECT OF MASS ON MECHANICAL PROPERTIES

The slower cooling that occurs with heavy as compared with light cast sections causes a reduction in mechanical-strength properties over the cross section. The center of the heavy section is apt to have large grain size, inclusions or voids, low density, and possibly, in steel, carbon segregation. All these characteristics promote a reduction in strength and ductility, in the heavier as compared with the lighter section in the as-cast condition. The variation is somewhat reduced in nonferrous metal sections that have been annealed, and can be practically eliminated in steel castings where grain refinement may be obtained through heat treatment.

The mechanical properties to be accepted in the metal of a casting are covered by purchasing specifications when strength is a requirement. To determine whether a given casting meets specifications, it is customary to test sample metal specimens taken either from coupons cast on the part itself, or from test coupons cast separately but from the same melt. These coupons are generally placed favorably for casting, and the feeding of the metal to them

is better than to the rest of the casting. As a result, the strength and ductility of the test bars are superior to the properties that are obtained in thicker sections of the casting.

15.14. SECTION THICKNESS AND DIMENSIONAL TOLERANCES

The best practice is to use wall thicknesses that can be poured without danger of incomplete filling out, and that will provide the necessary strength or weight. Section thicknesses should be proportioned to the area to be run and should be related to the adjoining sections, particularly those above and below it as the job is poured.

Steel. Where the over-all dimensions are not too great, steel castings with wall thicknesses as low as $\frac{1}{4}$ in. are poured regularly in many steel foundries. The minimum wall thickness is $\frac{3}{16}$ in. or a little less, depending on the design of the casting. For best properties, such as are necessary in pressure castings and highly stressed castings, the minimum thicknesses are at least double these figures. Over 70 types of low alloy steel are cast commercially today, and at least half that number of straight carbon steels.

Gray Iron. Gray-iron castings are made in a wide variety of section thicknesses. The white irons may become gray if poured into heavy sections, whereas gray irons may become white if poured into very thin sections. Soft gray cast iron (ASTM class 20, 25, 30, 35 plain gray irons) may be poured into $\frac{1}{8}$ in. sections and retain its grayness. Cast iron with a tensile strength in a 1 in. section of over 40,000 lb per sq in. (ASTM Class 40 plain gray iron and alloy iron ASTM classes 40, 50, 60) may be hard and white at the corners and edges if poured in sections thinner than $\frac{1}{4}$ in.

Malleable Iron. Regular malleable iron is commonly cast white in sections $\frac{1}{8}$ in. in thickness although the average minimum section is approximately $\frac{1}{4}$ in. Castings of this material may be cast satisfactorily up to several inches in thickness, depending on other dimensions and the design of the part, by proper adjustment of the composition. They may range from a fraction of a pound to more than 1000 lb, although the greater proportion of malleable iron goes into castings under 25 lb in weight. Regular malleable irons are ASTM grades 35018 and 32510. Some short-cycle pearlitic malleable irons are ASTM grades 43010, 50007, 60005, and 70003.

Nonferrous. The minimum thickness for nonferrous castings varies with the alloy, size and intricacy of the casting, pressure re-

quirements, etc. Castings poured at excessive temperatures, to run extremely thin sections, generally are deficient in physical characteristics and should be avoided. With brass and bronze $\frac{3}{32}$ in. is considered the minimum satisfactory metal section. With aluminum alloys $\frac{1}{8}$-in. sections have been cast satisfactorily, although a minimum thickness of $\frac{3}{16}$ in. is preferable. Magnesium alloys may be cast to $\frac{5}{32}$-in. minimum wall, but since the low specific heat of these alloys results in a larger rate of cooling, extra-large risers and gates are needed, making the yield about 20 to 25 per cent. Synthetic sand, containing an inhibitor to prevent reaction between moisture and molten magnesium, is required, and sections must be given even more generous radii and change of section than for steel to limit microporosity resulting from the wide solidification range (see Chapter 8 for specific sand-casting alloys and their properties).

Foundry specialization in casting parts of high similarity, for example, engine cylinder blocks, has resulted in production to very close dimensional tolerances. For new work and small production, much larger tolerances are required because of the patternmaker's difficulty in estimating the effect of shape on shrinkage. The customary rule is to allow half the shrinkage for the metal involved. On large dimensions this allowance will range from $\frac{1}{32}$ to $\frac{5}{16}$ in. per foot. Small as-cast dimensions cannot be held to these limits because of the variations that occur in removing the pattern. For small parts, the customary minimum tolerances for critical locations on the same side of the parting line are:

Metal	Min. Tolerance, Total, in. per ft
Gray iron	$\frac{1}{16}$
Malleable iron	$\frac{3}{32}$
Cast steel	$\frac{5}{32}$
Aluminum	$\frac{5}{64}$
Magnesium	$\frac{11}{64}$
Brass	$\frac{3}{32}$
Bronze	$\frac{1}{8}$

15.15 DESIGN DETAILS

Bosses. Bosses are often located on a wall of a casting and should be so designed that a heavy section of metal leads to the riser. This is illustrated in Fig. 15.7, as with *A* and *B*. No such provision is made for bosses *C* and *D*, and internal or external chills would be required to prevent a shrinkage cavity in them. These two bosses

are also more expensive to mold, because they have to be made either by use of a core or by loose pieces on the pattern. They cannot be drawn with the pattern as can the bosses A and B.

Ribs. Ribs are used primarily as stiffeners and reinforcing members. They not only increase the tensile strength and stiffness of the casting, but if properly designed and located in difficult castings, serve to check the possibility of hot tears or cracks during
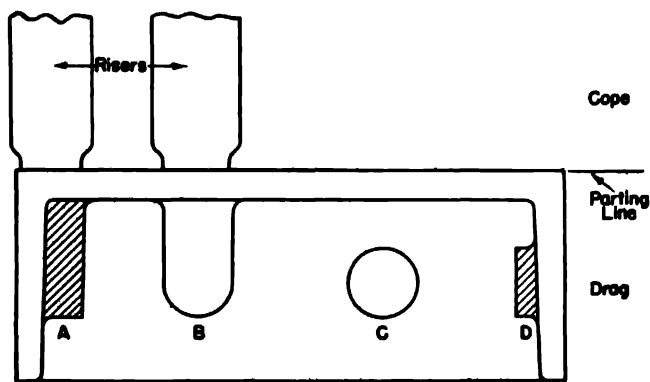
FIG. 15.7. Bosses should be designed with a heavy section leading to the feeding source, as at A and B. In C and D no such provision has been made, and either an internal or an external chill would be required. In addition, bosses C and D would not draw with the pattern, but would have to be made with loose pieces or a core.

solidification. Their function, in this respect, is to solidify earlier than the section which they adjoin. They then act as a bond to prevent cracking, and as conductors of heat to promote cooling of the section involved.

The relationship of rib section to main section should be such as to permit, as far as possible, a uniformly graded metal section. Where feasible, heavy rib intersections should be staggered (as in Fig. 15.8) to avoid local increased section thickness and the consequent possibility of internal shrinkage. Fig. 15.9 shows three types of rib design for aluminum-alloy castings. The tendencies of large, flat areas to distort when cooling from casting temperatures may be eliminated by ribs designed and located properly.

Wide ribs located perpendicular to rim or body sections should be cored out at the corner section to prevent the hot spot which would occur there (see Fig. 15.10).

Fillets. Properly proportioned fillets at all intersections materially increase the strength and soundness of castings. They also reduce costs from unavoidable foundry scrap due to shrinkage cracks and erosion of sand at sharp intersections.
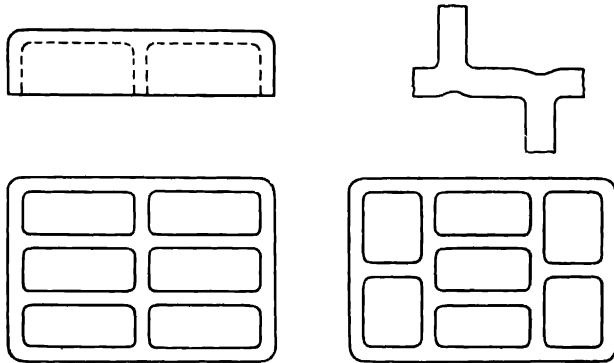
Fig. 15.8. Design of base plate (left) modified by staggering ribs (as at right) to eliminate *X* junctions. Note rib detail at top right. Staggered ribs also reduce distortion caused by shrinkage.

Sizes of fillets desired depend upon (*a*) metal used, (*b*) shape and thickness of the wall section, and (*c*) size of the casting. Fig. 15.11 illustrates an iron casting incorporating good fillet design.

Deep Pockets. Deep pockets and small recesses that complicate drawing the pattern or lifting the cope should be avoided, if possible. When used, they should be tapered and made as large as permissible.

Inserts. Metal inserts are occasionally cast into sand castings when properties not possessed by the cast metal are needed. A good knurl

(a)   (b)   (c)
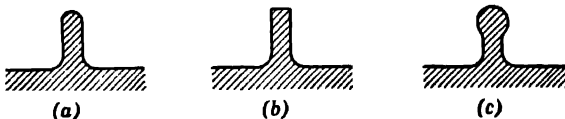
Fig. 15.9. Three types of rib design for aluminum alloy castings: (*a*) poor because of high fiber stress at extreme outer edge, (*b*) satisfactory, (*c*) preferred if molding procedure is not unduly complicated.

or groove should be used in the insert to provide the required mechanical bond. Sufficient metal should also be allowed around the insert so as to avoid foundry difficulties. Inserts will act as chills, and this action should be considered in their design.

Cored Holes. In steel castings, small holes that require a machined finish usually are drilled and not cored. Sometimes it is desirable or necessary to core out small holes, which are drilled later, to avoid shrinkage cavities in the bosses. Small and large holes usually are cored when no machine finish is required, provided the tolérance is at least $\frac{1}{16}$ in. on the diameter. Large holes that require machined surfaces frequently are cored and subsequently bored to dimension.

Where the design calls for the use of cores, provision must be made for anchorage of the cores to avoid shifting or lifting (floating) of them. They should be supported and anchored by core prints whenever possible, but metal supports can be used as an alternative. One type of metal support is a chaplet. It is used particularly with internal cores as illustrated in Fig. 15.12. Chaplets are to be avoided, as they constitute a potential point of weakness in the casting, and in steel castings such affected sections must often be chipped out and the hole filled by welding.

Fig. 15.10. Elimination of shrink cavity, *X*, in spoke *a-a*, by coring out junctions of spoke and rim of pulley or gear blank as in spoke *b-b*.

Fig. 15.11. Cast-iron end shield and bearing bracket illustrating generous use of fillets.

Internal cores also require provision for venting. Sometimes the design will permit them to be vented through their core prints, but extra prints may be required if the original ones designed are not adequate. These extra prints may also be required to facilitate removal of the core sand from the finished casting. The difficulties in-

troduced by internal cores both in making the core and in handling it in the foundry make it advisable to avoid their use when another design will serve as well. It is also good practice to avoid the use of

(a)   (b)
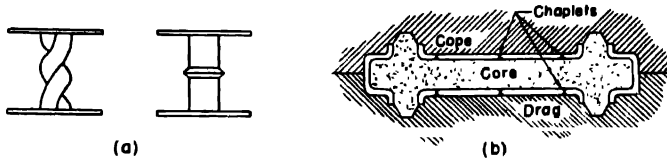
FIG. 15.12. (a) Two designs of chaplets and (b) an illustration of their use on an internal core.

dry-sand cores in green-sand molds when green-sand cores can serve or a change in form can eliminate need for a core.

Where there is the possibility of assembling a core upside down or backwards, a locating or indexing lug or form should be used so that the core can only be placed in the correct manner. If several cores are needed, it is desirable to use duplicates when convenient, thus saving core boxes.

15.16 FINISHING

After the casting has cooled, it is removed from the mold by either manual or mechanical means. The cores are cleaned out, and risers, gates, fins, and other excess metal are removed by flame cutting, arc cutting, sawing, chipping, or by hammering with a sledge. The rough surfaces are then dressed with a grinding wheel. High-velocity washing may be used to remove adhering sand. Objectionable surface scale may be removed by sand or grit blasting. Barrel finishing may also be employed on small pieces. Some parts, particularly large castings, are stress-relief annealed before blasting or washing.

The cost of cleaning a casting depends on the simplicity of the design, on the method of molding, and on the metal. Often on large, complicated castings, small cores surrounded by heavy sections of metal have a tendency to fuse on the metal, forming a substance as hard as glass and almost impossible to remove. Although this effect can be overcome to a certain extent by the use of cores made from silica sand or zircon, these materials are not generally used, and therefore small cores surrounded by heavy metal should be avoided. Steel requires the largest risers because of the greater shrinkage and so, in general, requires more expense for cleaning excess metal. The weight of metal in a finished casting ranges from 40 to 80 per cent of

the metal poured. This ratio is spoken of as the *yield*. It is lower for steels than for iron and other metals except magnesium, and is lower for pressure-tight castings than for structural work.

From the suggestions already made for the design of castings, it is apparent that cooperation can result in quality maintenance and improvement. It is not as readily apparent that cost and appearance can also be controlled by mutual consideration of the problem. The proportion of the cost of the foundry operation which is attributable to finishing may range from 25 to 75 per cent of the total. This cost may be limited by designs in which (a) the parting line junctions are minimized and simplified, thus minimizing irregularities in casting contour, dimensional variations, poor appearance, and risk of defective castings; (b) risers can be located with respect to variations in metal sections so they introduce as little distortion as possible during cooling, and are accessible for removal; (c) the surfaces to have the best finish are in the drag portion of the mold, and the in-gate, molding materials, and risers are all located so as to give best appearance; (d) the junctions for assembly or weldments are stategically located.

These foundry techniques can only be applied by the foundryman if he is fortified with a knowledge of the use of the casting, its control sections, vital dimensions, and important surfaces. Such information also facilitates the construction of the pattern. Sometimes the patternmaker can suggest ways to avoid the necessity for patterns "to the other hand," i.e., right and left patterns. He can often influence the dimensional accuracy of the final casting by proper use of the directional properties of wood. And, of course, his choice of materials (hard or soft wood, metal, etc.) affects the life of the pattern and thereby the quality of castings produced from it. Other modifications may make possible the elimination of core boxes, incorporation of pattern draft into the design, and elimination of ever troublesome chaplets and chills.

15.17 INSPECTION

Depending on the application of the casting, sections of it or test bars cast at the same time may be tested for mechanical properties. If many castings are to be made, sample castings may be tested to destruction to determine freedom from imperfections. The trend of employing castings for relatively high-temperature, high-pressure service has also introduced radiographic methods for nondestructive examination of the interior of castings. (See Chapter 23.) Subsur-

. face defects in steel or one of a few other alloys may be repaired by chipping out the defect and then refilling by welding. Unfortunately, many metals, including malleable iron, gray cast iron, and heat-treated aluminum alloys, cannot be repaired in this way without special techniques and possibly a serious loss in strength.

Machining, grinding, and quenching cracks at or near the surface of castings may be detected by either a magnetic or a fluorescent test method. (See Chapter 23.) When castings must be pressure tight, a nondestructive pressure test may also be employed. All the parts or openings are blocked off, and the casting is filled with water, air, oil, or kerosene under pressure and maintained for some specified length of time, while the casting is studied for leaks that might develop. Testing a casting for cracks, defects, or porosity by air is apt to be hazardous, particularly if the pressure applied is very great.

15.18 CONCLUSION

The casting process is subject to a great number of variables. Some of them are (a) the great proportion of handwork involved, (b) the control of molten-alloy composition and temperature, (c) the type of equipment available, and (d) the kind and quality of molding material available. The foundryman attempts to control these factors and their mutual effect on shapes, sizes, sections, junctions, ribs, bosses, fillets, etc., to produce sound castings at low costs.

In the absence of the designer's understanding of the influence of the design on casting quality and casting costs, the foundryman is often called upon to produce exceptionally tricky and intricate castings. Sometimes in desperation or perhaps because of pride of workmanship, he may endeavor to cast such a design. A clever foundryman can, and often does, produce exceptionally difficult castings. But his chances of duplicating this feat would be greatly increased if he and the designer would cooperate in considering modifications in design that would lead to simplification of the casting procedure and would minimize the hazards involved.

It is emphasized that the ideas suggested on design of sand castings, although adequate for many design problems, *cannot and should not take the place of a cooperative study of the design by the foundryman and the designer*, and adoption of those changes which prove to mutual advantage.

Casting in Other Nonmetallic Molds

15.19 PLASTER-OF-PARIS CASTINGS

A plaster mold, like a sand mold, produces only one casting and is then destroyed. The advantage of the plaster mold is therefore found in quality of its product rather than in added permanence of the mold. The castings made by this method have superior surface finish, better dimensional accuracy, finer detail, and a more solid structure than sand castings, although at a higher piece price before machining.

Plaster has been used as a molding material and for cores for several centuries, but the above advantages were not realized commercially until developments since 1937. The plaster used is composed of 70–80 per cent gypsum plaster (calcined calcium sulfate), 20–30 per cent fibrous strengthener (magnesium silicate), and a small percentage of impurities (salts and hydrochloric acid) to accelerate the setting of the mixture. Water 50 per cent in excess of the amount required to set the plaster is added. This plaster mix is poured around the pattern, and when it reaches the semiset state, the pattern is removed, forming the mold cavity. A match-plate pattern is used, permitting the cope and drag to be made separately. The match plate is fastened to the snap flask (flask with hinge) and may contain as many as 20 different or identical individual patterns along with gates, risers, etc. These individual patterns are made from metal and may be added or removed at will, thus making substitution economical.

After the mold impressions are completed, the flask with match plate is removed, and the cope and drag halves are baked separately. This operation drives the moisture from the plaster and leaves a labyrinth of small connected holes in the material at the points previously occupied by the excess water. These holes serve to vent the air inside the mold and the gases introduced by the molten metal as it is poured.

If cores are to be used, they are made in the same way as the mold, baked separately, and assembled with cope and drag after the baking period. The mold is then ready to pour.

The plaster-of-Paris process is usually limited to metals with a melting point not exceeding about 2100 F (except magnesium), but variations of this process are commercially available to cast higher-melting-point metals (up to 3000 F) such as stainless steels. The most popular metals in decreasing order of their use are yellow brass (Muntz metal or naval brass), aluminum bronze (4.5 per cent iron),

manganese bronze, silicon bronze, and occasionally aluminum (Alcoa 43 or 355). Red brass and naval bronze do not have a good surface when cast in plaster molds.

The plaster does not stick to flat surfaces but may adhere to cored or indented sections, and in such cases is usually removed by high-pressure water-stream washing.

Owing to the low thermal conductivity of plaster of Paris in comparison with sand or metal, the molten metal in molds of the former is kept fluid longer. This permits casting sectons much thinner than in sand casting or even metal mold casting (0.040 in. thick for 2 sq. in., 0.065 in. for 6 sq in., and 0.093 in. for 30 sq in.) and there is less danger of internal porosity. However, the structural strength of castings made in plaster-of-Paris molds is likely to be somewhat lower than that of metal mold or sand castings, especially in those alloys which are given to grain growth, like aluminum.

Tolerances produced by this method compare well with metal mold casting. Limits of ± 0.010 in. are usually held on over-all dimensions and ± 0.005 in. on small dimensions. External draft may be limited to $\frac{1}{2}°$, and internal draft from $\frac{1}{2}$ to $3°$, depending on the complexity of the contour.

Typical applications of plaster mold castings are plumbing fixtures; railroad, automotive, and domestic hardware; ball races; gears of all sorts; handles, cams, and levers; covers and boxes; brush holders, terminals, etc. The plaster mold castings are particularly attractive for moderate production parts that would require considerable machining if made in sand, but on account of their limited production would not justify the high tool cost of metal molds. They compete more favorably with brass and bronze metal mold castings than with aluminum.

15.20 LOST WAX CASTING

The casting of art statuary, dental plates for false teeth, etc., is difficult by regular methods because of the complicated core work. To eliminate the necessity for cores, use is made of a special molding method and of pattern materials that will melt at baking temperatures of normal sand or plaster molds. Such a method was used for making art statuary many centuries ago in China and Japan, and as late as the middle of the sixteenth century in Europe. It is known as the "lost-wax" process. Commercial application of this method has been accelerated by gas turbine applications of its products since 1943.

The first step is to make a pattern mold of the original model produced by the sculptor. Glue molds were used at one time, but present-day applications utilize plaster molds for large statuary and cast low-melting-point metals (lead alloy usually) for wax patterns. Machined metal molds are used for some plastic patterns. The external mold is closed and filled by gravity pouring or external-pressure injection of pattern material. If a thin wall casting is desired, the mold is upended after a short chilling time and the wax not solidified is allowed to run out. The solidified wax forms an accurate duplicate pattern of the original model.

This pattern is finished free of fins, and any desired detail is added. It is then equipped with gates and vents in the form of wax rods of appropriate diameters. The pattern may be sprayed or dipped with refractory powder or a fine silica-flour mixture to improve finish of the mold face. It is then ready for preparation of the mold.

The mold in which the metal part is to be cast is started by pouring investment (molding material) around the outside of the wax figure and allowing it to harden. Plaster is used for metals which melt at 2100 F or below, and silica base investments with a bond of an "organic" silica are used for higher melting point alloys. Various mixtures of plaster and silica with water are used to obtain the desired shrinkage for accurate dental parts. The mold may be poured under vacuum to reduce air bubbles. It is then baked in the inverted position from ½ to 24 hours. The wax pattern melts and runs out, and any retained wax is burned out by the baking heat which also prepares the investment for casting. (With plastic patterns, such as polystyrene, the pattern is volatilized and burned out.) The mold is ready to pour at the completion of the baking operation. Gravity casting from a ladle is used for large art forms, and dental or jewelry parts, but air-pressure casting from special machines and centrifugal casting with a vertical axis are typical methods employed industrially.

An industrial application of this process is the production of small metal parts of complicated shapes, or of metals which cannot be forged, rolled, or machined by the usual factory methods. Casting the parts to size with good surface properties is desired. By proper choice of an investment compound, it is possible to have the investment expand by preheating just as much as the metal will shrink during cooling, and it is thereby possible to control closely the size of the finished casting. Tolerances of ±0.005 over-all and ±0.002 inch on small dimensions can be obtained. Sizes at present are limited by

equipment to a 6-in. flask diameter and to $\frac{1}{2}$-in. wax thickness. Castings of 1 lb weight are most common, but some have been produced to 5 lb. The term "precision casting" is often applied to this process.

A related application of these techniques is the preparation of dry-sand cores which must contain passages of some curving contour. Such a core might be needed for casting the blades in an integral centrifugal fan. The core is prepared by building up a model of the section to be cast by the core. This model is made from an alloy of low melting point such as Wood's metal or Cerrobose. Sand for the core is tamped in and around the fusible metal structure, and when complete, vented, etc., is baked at a temperature below the melting point of the structure. After the core is dried properly, the temperature is raised, allowing the metal to melt and run out, and leaving a core with which the integral part can be cast.

15.21 ELECTROFORMING

In this process a plaster outer mold is made from the model or pattern and a fusible alloy or rubber is melted and poured inside. The fusible alloy or the rubber is solidified and removed from the mold, and then its surface is electroplated with copper, iron, or any other metal that can be plated. For plating rubber it is necessary to precoat the surface by depositing silver chemically, or by rubbing graphite or graphite and silver over the surface, so that it can carry current. Once the plating is prepared, the fusible metal is melted out, or the rubber is stretched and deformed out. A feature of the plated part is excellent detail and no shrinkage from the original. Depending on the purpose, the electroformed part may be used as the product, or it may be backed with some metal and used as a die for forming operations such as embossing, die casting, and engraving. It may also be used for molds for glass, ceramics, rubber, plastics, foodstuffs, soap, candles, hot-water bottles, candies, artificial wood, and leather surfaces.

15.22 CASTINGS IN OTHER MATERIALS

Both wood and paper have been used for molds of sufficient permanence that they can be used for a small number of duplicate castings, provided that only low-melting-point alloys are cast in them.

Wood is used for molds of printing designs. The pattern is burned in the end grain of a dried wooden block by shaped steel tools heated to a red heat. The bottom of the impression forms the printing design on the casting. Since the width of the impression is not greater than

$\frac{1}{32}$ in., there is not sufficient metal to give heat enough to damage the impression. As many as 50 to 100 castings can be produced.

Paper molds are made from several layers of tissue paper pasted together and backed by damp unsized paper. They can be used as molds for full pages of type, including illustrations. When dry, the mold thus formed is mounted on an iron support to receive the molten metal.

Shell Molding. In 1947 the shell-molding or Croning casting process was introduced into the United States from Europe. This process produces castings somewhat better than sand castings at a lower cost, if quantities are moderate, through mechanization of a considerable part of the molding operation.

A hard, smooth mold of controlled permeability is made by dropping molding material upon a heated metal pattern previously coated with a parting agent. Fine sand and thermosetting phenolic resin are used for the molding material. Additives include zircon sand to reduce "burning-in," and liquid agents, such as kerosene, to reduce segregation and dusting. The heat of the pattern, approximately 500 F, causes the molding material to adhere, forming a shell approximately $\frac{1}{4}$ in. thick around the pattern. Temperature of all parts of the metal pattern must be uniform, 30 F differential being the usual limit. The green mold is cured in an oven while on the pattern, then is stripped from the pattern, and the cycle repeated to form additional shell molds. Machines are available to perform all these operations at rates from 6 to 10 times as fast as duplicate sand molds may be made.

The pattern is made from a metal that will withstand 800 F and has high heat capacity, low expansion coefficient, corrosion resistance to materials evolved in the sand cure, abrasion resistance, and mold-release qualities. Cast iron, gray iron, low-distortion die steel, and high-copper alloys have been successfully used. The pattern is attached to a metal back plate, usually of the same material. Sizes for pouring basin, sprue, runner, and in-gate are experimentally determined, using putty, wood, etc., and are then incorporated into the metal plate. Alignment pins and alignment sockets are also incorporated into the plate. Cores, if required, are blown solid from urea resin and sand up to 4 in. diam, and larger ones are made as additional shell molds.

A complete mold is made by assembling two shell mold halves, either identical ones from the same pattern or matching ones from two

patterns. Excellent alignment is obtained because of the pins and sockets integral with the molds. In early work the molds were held together with clamps, or bolts for the heavier parts, and a backing of steel shot was employed during pouring of the mold. Since 1950 molds have been assembled by curing urea resin adhesives on the mold faces under heat and pressure, and molds for castings under 25 lb are poured without backing.

Except for high-leaded brass, any metal that is suited for sand casting may be cast by the shell process. Size of castings produced has been limited by equipment to 70 lb for cast iron, 50 lb for nonferrous alloys, and approximately 1 lb for mild steel, which is subject to gas defects. Castings up to 400 lb have been produced in Germany.

Advantages of the process are:

1. Greater accuracy is obtained, with tolerance of 0.003 in./in. maintained in the mold face and 0.006 to 0.012 in./in. across the mold joint. Accuracy compares to lost wax, investment, and aluminum die casting methods.

2. Only 5 per cent as much sand is handled as for sand casting, and the sand may be reclaimed by burning out the plastic.

3. Smooth mold faces offer less friction and permit thinner sections, sharper detail, higher yield, and/or lower pouring temperatures.

4. Mechanized equipment permits preparation of good molds at high rate by unskilled labor, often at rates up to 35–40 per hr.

5. Low draft may be used; 1 degree is maximum, 0.5 degree usually suffices, and even less may be employed for low-draft parts.

6. Molds may be stored for long periods, if necessary.

7. Cleaning of castings is reduced because there is little burned-in sand, gates and risers are small, and little sand is involved.

8. Machining is reduced to 50 per cent compared to sand castings, and many parts are only polished or ground because of fine finish and good accuracy.

9. Less capital investment is required than for other methods of producing moderate quantities of castings. The metal pattern cost, however, penalizes the process in comparison to sand castng if only a few castings are to be made.

The shell-molding method gives promise of wide use because of the excellent castings obtained, the substantial reduction in costs, and the possibility of using these molds for centrifugal castings.

METAL MOLD CASTING
by D. BASCH and J. F. YOUNG

15.23   METAL MOLD PROCESSES

Sand, plaster-of-Paris, and precision-casting molds are single-purpose molds; that is, they are completely destroyed when the casting is removed.   Thus, a new mold must be prepared for each casting to be made.   Considerable savings in labor and material may be realized if a "permanent" mold is made which lasts for the required number of castings.   Such permanent molds are made from metal.   They are not recommended when only a few castings are to be made, because the cost of the metal dies would greatly exceed the cost of the individual sand or plaster molds.   In addition, the absence of metals that will withstand very high temperatures and the difficulty of making large metal molds make them unsuitable for large castings or for alloys of high melting temperatures.   The metal-mold processes are more favorably used for small- and medium-size castings made in large quantities.

The methods of casting which utilize metal molds are classified as follows:

1. Permanent-mold casting.
2. Semipermanent-mold casting.
3. External-pressure casting:
    (a) Die casting.
    (b) Cold-chamber pressure casting.
4. Centrifugal casting.

The desirability of each of these methods depends on the design of the part, the metal used, the quantity of castings to be made, and the effect of the quality of the casting on subsequent manufacturing costs.   To evaluate these points better, each method will be considered separately.

15.24   PERMANENT-MOLD CASTINGS

In this casting method, fluid metal is poured by hand into metal molds and around metal cores.   The only pressure applied is that of 2 or 3 lb per sq in. exerted by the head of metal in the pouring gate, thus the term "gravity die casting" used to designate this process in England.   The molds are usually held together by C-clamps, although

sometimes they are closed and opened by a screw or a toggle mechanism.

Both iron and nonferrous metals may be cast. Dies for the alloys of very low melting point are made from bronze (rubber for tin alloys). Iron and steel molds are used for the higher-melting-point nonferrous castings. Metal cores may be made from other castings or from wrought materials. For casting permanent mold iron, steel molds are coated with refractory material. The latter molds are usually cast with allowance for machining and refractory material, which helps reduce erosion and checking. The coating must usually be dusted with carbon between uses and renewed every day. The casting is never as smooth nor as accurate in dimension as castings that contact the polished metal die surfaces, but they are superior to sand castings. They also have better structure than sand castings and greater freedom from steam and gas holes.

For making iron castings of this type, turntables on which a number of metal-mold units are mounted are frequently employed; and the individual operations—such as coating the mold, placing the cores, closing the mold, pouring, opening the mold, and ejection of the casting—are performed as each mold passes certain stations. A typical composition for permanent mold iron is 3.4–3.6 per cent carbon, 2.4–2.6 per cent silicon, 0.70–0.90 per cent manganese, 0.30 per cent max phosphorus, 0.10 per cent max sulfur, and balance iron. Strength properties are equivalent to pearlitic gray iron at the mold face and drop off in sections thicker than $\frac{1}{2}$ in. The castings are usually annealed to avoid white iron in any corners which may not have been properly heated (preheating), coated with refractory, or smoked with carbon. The anneal also relieves any strain that may remain.

Of the many metals suitable for this type of casting, aluminum and its alloys are used the most, magnesium next, and the copper-base alloys other than the brasses are third (see Chapter 8). Aluminum-base metals are molded this way, even though the lack of pressure reduces tensile strength somewhat, because there is less porosity in the casting than when made by other methods. Some heat-treatable alloys are cast, since heat treatment offers less difficulty than with die castings, which are subject to porosity and blistering. Copper-base materials include the bronzes, particularly the high-iron aluminum bronzes which are gaining in importance for gears, bushings, etc. Iron is perhaps fourth in importance. Lead is permanent mold cast for battery grids and connectors, but the alloys of lead, tin (when available), and zinc are used chiefly for permanent mold slush castings.

In the slush casting process the metal is held just long enough in the metal mold to permit the outer "skin" to harden. Then the mold is up-ended and the liquid core of the casting is allowed to run out, thus leaving a hollow, thin-walled shell. The thickness of the wall can be controlled by the pouring temperature, and the time interval between pouring in and out. The inside wall contour and the wall thickness are always irregular. This is illustrated by the slush casting shown in Fig. 15.13. Typical products made by the slush process

FIG. 15 13. Zinc slush casting sawed in half. Note irregular wall thickness.

are toys, handles, teapot spouts, fancy borders and trimmings, novelty clocks, candlesticks, lamp stands, electric-light fixtures, and ornamental objects that may be finished in silver, gold, or bronze.

A variation of the permanent-mold process for producing castings with hollow interior is the use of a core or plunger which is forced into the mold after a controlled amount of fluid metal is poured in. The plunger causes the metal to fill the mold cavities with same pressure giving good detail. This method is called "as-pressed" casting, or Corthias casting, after its inventor, and is used mainly for simple ornamental castings.

The permanent-mold method provides castings having these advantages: (1) dense, fine-grained structure, free from shrink holes or blowholes; (2) relatively low tool charges; (3) lower mold cost than for other metal-mold methods to be discussed; (4) better surface and closer tolerances than provided by the sand-cast method.

On the other hand, the method has these limitations: (1) inability to maintain as close tolerances and as thin sections as will the external-pressure or plaster-of-Paris casting methods; (2) yellow brasses, which are high in zinc, are difficult to utilize because zinc

oxide fouls the mold or dies; (3) the production rate is slower than for the same parts made by other metal-mold methods.

15.25 SEMIPERMANENT-MOLD CASTINGS

This method is the same as that for permanent-mold castings except that sand cores are used at some points instead of metal cores. The use of sand cores results in lower tool cost and also allows cored
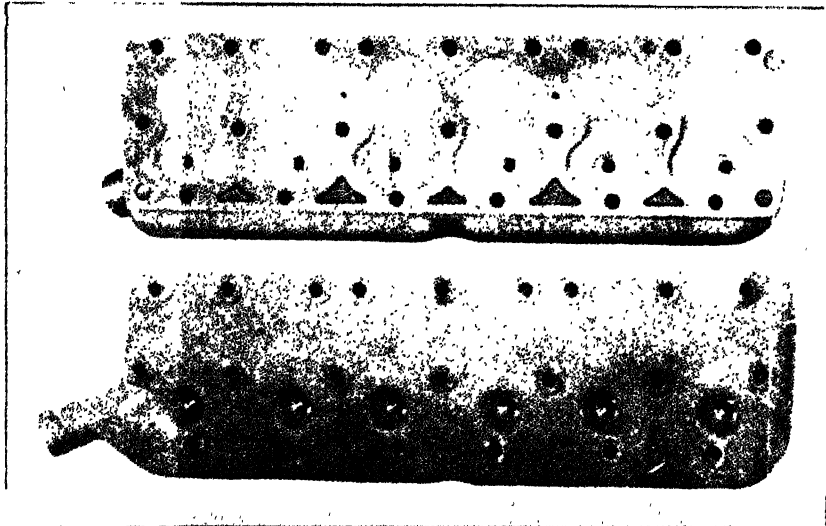
Fig. 15.14. Semipermanent mold aluminum cylinder head typical of those produced in vast quantities for many internal-combustion engines. (*Courtesy Aluminum Co. of America.*)

openings of irregular shape, or undercuts of such type that metal cores would be too costly or too difficult to handle (large or deep, etc.) on a production basis. Most applications make use of this latter possibility. Fig. 15.14 is an example of a semipermanent-mold aluminum casting.

The metals suitable for casting by this method are the same as for the permanent-mold method, but the speed of production is somewhat reduced.

Another disadvantage of the method is that the structure of the metal around the sand cores and the dimensional inaccuracies, core shift, etc., are the same as for sand casting. The advantages of casting tolerances, density, appearance, etc., as for permanent molds, exist

only in the section cast against the metal mold. Several castings made by permanent and semipermanent metal molds are illustrated for comparison in Fig. 15.15.
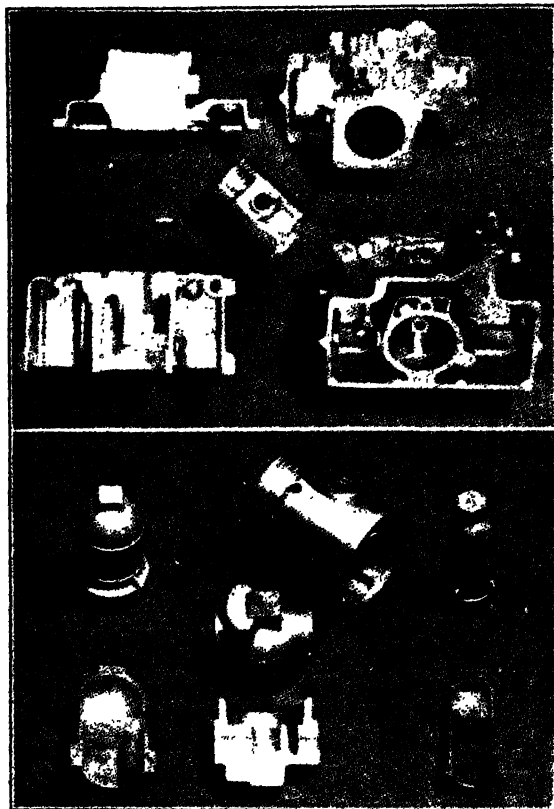
Fig. 15.15. Examples of semipermanent- and permanent-mold castings. Note cut parts showing the contour of the cross section. (*Courtesy The Permold Co.*)

15.26 EXTERNAL-PRESSURE CASTINGS

In this process, highly fluid metal is forced under considerable external pressure into metal molds, the pressure being maintained until solidification is complete.

The metal molds, or dies, comprise at least two blocks of alloy steel, each containing a part of the cavity. They are locked together while the casting is being made, and drawn apart when it is ready for ejection. One-half of the die (next to the injector nozzle) is stationary, and the other half moves on a carriage. Both halves are some-

times artificially cooled to hasten the solidification and the removal of the casting from the die.

The casting remains in the movable half of the die as the die opens. This half often contains core pins or other male portions upon which the casting shrinks in cooling. Mechanically operated ejector pins push the casting off these pins and projections and free of the die.

Aside from changes in dimensions of the die block resulting from heat expansion and contraction and from minor wear on die surfaces, the dimensions of the cavity remain substantially fixed, thus facilitating repetitive production of castings having small-dimensional tolerances.

The many different machines used commercially to open and close the dies, introduce the molten metal, eject the casting, etc., may be divided into two classes: (1) those in which the casting mechanism is constantly immersed in hot molten metal; and (2) those in which the mechanism is immersed only for short intermittent periods.

Castings made by machines of the first class are called "die castings" or "hot-chamber pressure castings"; and those of the second, "cold-chamber pressure castings." Both classes are called "squirt castings" (*spritzguss*) in Germany, and "pressure castings" in England, where the term "die casting" is applied generally to a casting made in a metal mold by any of the methods. The terminology used in the United States has been established too firmly, however, to expect change.

15.27 DIE CASTINGS

Die castings are produced in machines that consist basically of a basin holding a considerable quantity of molten metal (enough for several hours' production and continually replenished), a metallic mold or die, and a metal-transferring device that automatically withdraws a certain amount of molten metal from the basin and forces it under external pressure into the die.

The oldest form of die-casting machine is the so-called piston machine shown schematically in Fig. 15.16. Lead, tin, and zinc alloys containing aluminum (Zamak alloys) are handled in this machine at pressures ranging from a few hundred to 5000 lb per sq in. The best practice for zinc-aluminum alloys is to use a minimum of about 1000 lb per sq in.

Aluminum alloys, pure zinc, or zinc alloys free from aluminum require a different type of casting machine since these materials rapidly attack the iron in the piston and cylinder and destroy the required

close fits. The gooseneck machine shown schematically in Fig. 15.17 was developed to eliminate this difficulty. In this machine the gooseneck serves as the device for transferring the molten metal from the metal container to the die opening. Air pressure applied externally
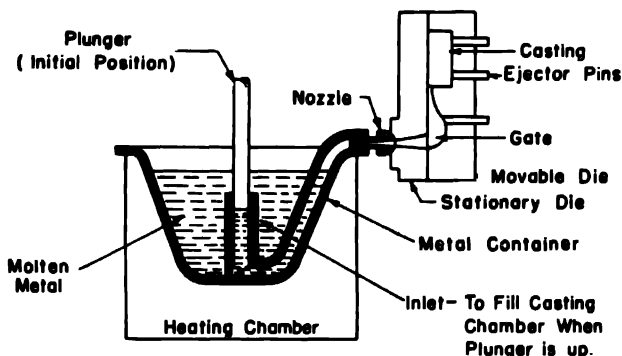
FIG. 15.16. Typical piston-type die-casting machine. The plunger, heating chamber, metal chamber, and die carriage are parts of the same machine.

forces the metal into the dies. The air pressure that may be applied is limited to a maximum of 700 lb per sq in. (350 to 550 lb per sq in. on the average). With Zamak alloys this results in a structure somewhat less dense than that from the piston machine.
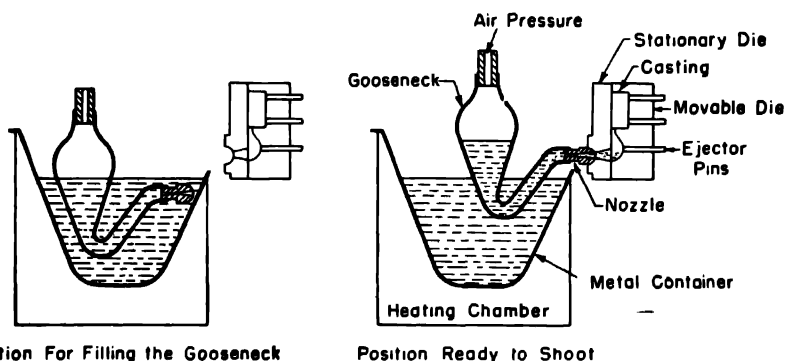
FIG. 15.17. Typical gooseneck-type die-casting machine. The gooseneck, metal container, heating chamber, and die carriage are parts of the same machine.

Aluminum, at its melting temperature, strongly attacks the iron in the gooseneck and the metal container, especially when in continued contact, with the result that the metal used for aluminum castings to be made with the gooseneck machine will practically al-

ways show an increase in iron content. This is a disadvantage, because iron in aluminum adversely affects the ductility, castability, machinability, and shock resistance. When the aluminum castings must contain less than 2 per cent of iron, they are frequently cast by the cold-chamber or the permanent-mold process to avoid this difficulty.

Both the piston machine and the gooseneck machine are limited to casting metals that have a melting point not exceeding 700 C. The strength of the machine parts operating in constant contact with the molten metal and at its temperature impose this limit. Even so, the pistons require repair on the average of once a production month, and the nozzles require replacement much more frequently.

Automatic single-impression machines have recently been developed for producing small zinc-alloy die castings in sizes up to 2 in., at weights up to $\frac{1}{2}$ oz, and with minimum wall thickness of 0.005 in. at tolerance of 0.001 in. per in. Cored holes must be 0.015 in. or greater and draft 0.003 in. per in. on inside dimensions and 0.05 in. per in. on external dimensions. The process is capable of 100 parts per min. Casting is completed so quickly that parts may be die cast around string or fabric without damage, offering interesting possibilities for small hardware, fasteners, and similar items.

15.28 COLD-CHAMBER PRESSURE CASTINGS

Cold-chamber pressure castings are produced in machines which are fundamentally different from the die-casting machines shown in Figs.
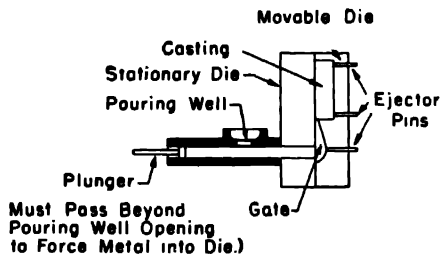
Fig. 15.18. Sketch of cold-chamber pressure machine. The plunger, cylinder, and die carriage are parts of the same machine. The melting pot and metal container are separate.

15.16 and 15.17, in that the molten-metal reservoir is separated from the casting machine. Just enough metal for one shot is ladled into a small chamber, or pouring well, from which it is forced into the die under high pressure (see Fig. 15.18). There is no limitation to the

pressures back of the metal, pressures as high as 16,000 or even 20,000 lb per sq in. being employed sometimes. Usually, however, lower pressures of the order of 3000 to 10,000 lb per sq in. are used to facilitate the mechanical problem of making the machine heavy enough to provide the locking and holding power to keep the two die halves together under the tremendous impact of the injected metal.

The relatively short exposure of the pouring well, cylinder, and piston to the molten metal permits casting of alloys of high melting point such as brass and bronze. It also minimizes the absorption of iron from these parts and thereby enables production of low-iron aluminum castings.

The added pressure is also important to the type and quality of castings that can be made. The greater the pressure back of the metal, the greater the compressive force to compact the metal structure as it passes through the pasty stage, and the greater the force to press the hot metal through narrow channels, into sharp corners, crevices, etc. Thus cold-chamber pressure castings give greater promise of close grain, nonporous structure, sharp outline, and extremely thin section than die castings. These results cannot be obtained, however, unless expert metallurgical and production control are exercised, and dies are most carefully gated and vented. Vents allow the air ahead of the incoming metal to be driven out of the die rather than to mix with the molten metals.

Besides castings of copper and aluminum alloys, the process is applicable to magnesium alloys and zinc alloys. Although the production speed of the cold-chamber process is less than that of the piston process (because of the ladling operation), the over-all speed is about the same because of the "down" time for maintenance in the die-casting process.

15.29 GENERAL CHARACTERISTICS OF EXTERNAL-PRESSURE CASTINGS

Aside from the differences mentioned in the last two paragraphs, all these castings share certain properties, although to a varying degree. They all have close tolerances, sharp outlines and contours, a fine, smooth surface, and high speed of production with low labor cost. They all have a hard "skin" with a softer core, owing to rapid chilling of the surface of the casting in contact with the artificially cooled metal mold. Consequently, machining the surface will disproportionately reduce the strength of the section and will cause warping

through release of internal stresses held in check by the skin as long as it is unbroken.

If the molten metal is introduced into the mold at high velocity, there is a tendency for the molten metal to trap air and oil vapor in the die and the occluded gases in the metal, as illustrated in Fig. 15.19. There is also some spraying action which permits oxidation of small metal globules. Both these actions promote a porous nonintegral core structure. Since machining such castings will reduce the leakage resistance to internal pressure, it is generally inadvisable to machine deeper than 0.010 in. max. Exposure of these castings to high temperature may produce blistering of the surface because of the expansion of gases trapped inside the casting by the rapidly hardening skin. This tendency limits use of these castings for cooking utensils or heating apparatus, and prevents use of metals which could be hardened by heat treatment.

Molds for castings of certain design have been filled in such a way that gas holes and globule oxidation are reduced if not eliminated. This method involves slow filling, to avoid squirting the metal into globules, followed by a pressure set to densify the structure. It has the advantage

Fig. 15.19. Sketch showing how air and vapor are trapped in a casting when the molten metal is squirted into the die.

of increasing strength and reducing blistering at elevated temperatures. These characteristics suggest that the method may have many applications for castings that must be heat treatable or used in relatively high-temperature applications.

Internal shrink holes are more apt to occur with die casting than with cold-chamber casting. They may be caused by:

(1) *Uneven Chilling.* The heavy sections shrink last, and if the metal between the heavy sections and the pressure at the sprue becomes frozen first, a hole (or a depression of the outside if the wall is weak) will result at the heavy section. Design can correct this.

(2) *Drossy and Sluggish Metal.* When a metal is contaminated with too much iron and other impurities, its flow becomes sluggish and it chills before its shrinkage is fully satisfied. Die-casting metal might contain impurities because of continued contact with the metal container.

Pressure or vacuum-filling techniques are often used to seal porous die castings for leakproof applications. Magnesium castings are almost always filled. Aluminum and zinc are filled to a lesser extent. The parts are first machined, then cleaned, heated to 250 F approximately to drive off solvents, cooled, impregnated usually with a thermoplastic resin, and then cured at 250 F.

Cold-chamber pressure-cast brasses and bronzes have not yet found the same wide popularity as zinc and aluminum die castings or cold-chamber pressure castings, although excellent products have been produced. The main difficulty lies in the high cost of the dies, since the tool-steel industry has not yet produced a steel for the dies that will last as long at the high temperature at which the cuprous alloys are cast as die steels for aluminum or zinc. Further, dies for zinc sometimes do not need heat treatment. Plaster-of-Paris and permanent-mold castings are still competing favorably with cold-chamber pressure-cast brass or bronze, except where production is so large and savings in machining due to the closer tolerances so considerable that the high cost of molds for the cold-chamber pressure castings can be absorbed. Competition between permanent-mold and die castings is mainly between alloys of the same metal rather than different metals.

15.30 DESIGN OF METAL-MOLD CASTINGS

Metal-mold casting involves the pouring and solidification of molten metal, as in sand casting, and the use of metal dies, as in plastic molding. Accordingly, the design of metal-mold castings gives rise to a combination of the problems encountered in designing sand castings and plastic parts, and makes use of many of the techniques already discussed for designing these parts. Of the many techniques mentioned, the following should be incorporated in the design of metal-mold castings, particularly external-pressure castings, whenever possible.

(1) For low die cost, parting lines should be in one plane, preferably at right angles to the tie bars that guide the movable half of the die.

(2) Both internal and external undercuts should be avoided when possible. Undercuts on the outer surface necessitate a separate slide.

Cores or male die parts cannot have undercuts without introducing complexities in die construction. Both types of undercuts increase die costs and production costs.

(3) Sections should be uniform, and any changes in section thickness should be made as gradual as possible. Fig. 15.20 illustrates two examples of designs modified to obtain more uniform sections.

(4) Section junctions should be joined by fillets, especially where these junctions are subjected to service stresses, because the fillets reduce stress concentration and give a crystalline structure which re-
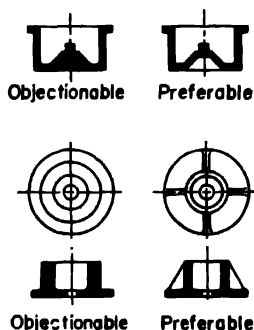
Fig. 15.20. Examples of design changes resulting in uniform sections.
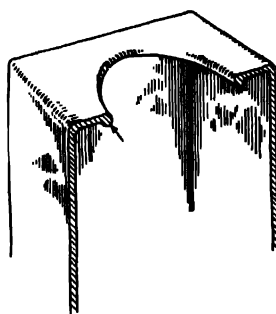
Fig. 15.21. Box showing use of a bead.

sults in stronger castings. Sharp corners in molds may also retard metal flow or cause eddies and trap air, thus proving disadvantageous from the casting standpoint.

(5) Ribbing is desirable on thin sections of considerable area, especially when flat, not only to give stiffness and to minimize warpage, but also to provide feeder channels of larger cross-sectional area. Without such channels, a large flat surface may not fill out, particularly when the die is cold.

(6) Ribs or beads may also be used to strengthen thin sections (Fig. 15.21) where trimming of flash is required. Such beads improve appearance, diminish chances of warping, and reduce trimming costs.

(7) Bosses and other heavy sections, when used, must be so designed that they can be fed with molten metal from the gate. Bosses isolated from the gate by a thin section will contain a shrinkage cavity, since their contraction cannot be made up with molten metal. Liberal fillets should be allowed where the boss joins the supporting sections. Bosses are often used around inserts to stiffen the casting

where the insert projects. Heavy bosses should be used around holes in which taper threads are tapped, to prevent the likelihood of the casting being split or cracked when a plug or connection is screwed in.

(8) Letters, numbers, trademarks, stippling, or knurling should, for low die cost, be raised on the die casting, and sunken on the die as for plastic parts. Undercuts should be prevented by putting engraved or lettered surfaces parallel, or nearly parallel, to the parting line, otherwise an extra slide or movement is required in the die. If it is undesirable for the lettering to be raised from the surface of the part, the whole lettered section can be sunk into the casting to the depth of the letters.

(9) The slenderness of core pins for bottomed and through holes must be limited as in plastic molding to prevent the pins from breaking or bending excessively under the action of the metal entering the die at high velocity and under high pressure.

(10) Although intersecting cores are often used successfully, their use is best avoided, if possible, because bending and wear may cause them to become misaligned.

15.31 DESIGN DETAILS FOR METAL-MOLD CASTINGS

Some other points which should be considered when designing metal-mold castings are discussed in the following paragraphs.

Cores. Aside from the slight difference involved in the cost of machining the cores, a cored hole may be cast square, hexagonal, splined, or of odd shape as cheaply as of truly circular section. In this respect, a die-cast piece with an odd-shaped hole is usually much less costly in quantity production than one made by other means than casting. A bushing with a splined external diameter is sometimes die cast and forced onto a shaft so that the expense or splining the shaft can be avoided.

The core should have its axis at right angles to the parting face, if possible. It is then parallel to the direction of motion of the die blocks, and is easily removed or the piece easily stripped from it. Cores can be pulled at any angle, but at slower production rates. Many types of mechanism, either manual or machine-operated, are adapted for this purpose. Some machines have more or less "standard" core-pulling mechanisms. Others require special rigging, special slides, or other special operating means, which may be a part of the die or of the machine itself.

Special Cores. Where undercuts are required, use may be made of collapsible cores. These are in several sections so designed and as-

sembled that a key section can be withdrawn easily, leaving the others
then free to be removed.   An example is the collapsible core arrange-
ment used for making a vacuum-cleaner housing (Fig. 15.22).   Some-
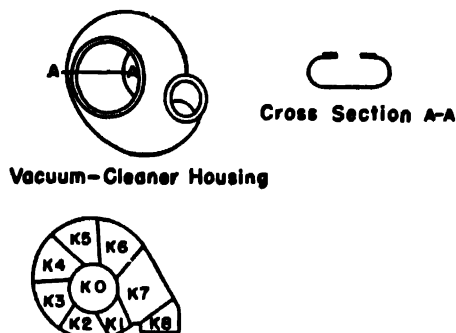
FIG. 15.22.   Collapsible core used for casting a vacuum-cleaner housing.

times crooked cores are made from loose pieces or knockouts designed
to clear the part when removed separately, but not as an assembly.
The kettle spouts illustrated in Fig. 15.23 are good examples.   For
other undercuts, straight cores may be combined with one or more
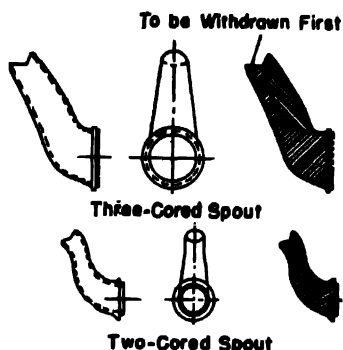
FIG. 15.23.   Coring for die-cast
kettle spouts.
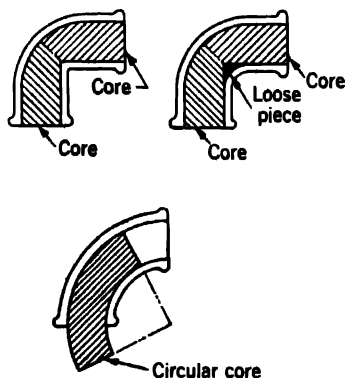
FIG. 15.24.   Cored elbows illustrat-
ing, at left, two methods of avoid-
ing use of a loose piece, at top
right.

loose pieces that are knocked out when the main core has been with-
drawn.   This type of core is illustrated in an elbow with an inside
fillet (Fig. 15.24).   The loose piece may be avoided by using a square

inside corner or by employing a core which may be rocked into place as illustrated in that figure.

Crooked channels from which cores could not be withdrawn are made by using a drawn tube, bent to the desired shape, as an insert and casting it in place. This is sometimes done to provide an oil channel from one point to another in the body of a casting, thus making it possible, for example, to feed two bearings from a single oil supply without external piping.

Although undercuts can be cast by these and similar techniques, they involve complications and often slow the casting operation. Sometimes the end justifies the means, but frequently the design can be changed to avoid the necessity for undercuts, as in Fig. 15.25, or the undercut may be machined rather than cast. An annular groove inside a hole is easily machined but difficult or impossible to core.
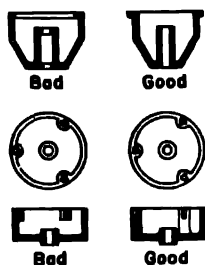
Threads. Internal threads are made by a stud core which must be unscrewed from the piece. This tends to slow production, unless some special provision is made on the machine or die to perform this automatically. It is usually cheaper to tap all holes that are to be threaded. When the holes are not too large, they may be cored to the root diameter (minus draft or taper) and then require no drilling before tapping. Sometimes it pays to punch or drill holes for tapped threads rather than to core them. This is especially true for small holes that would leave a thin flash or fin that would have to be cleaned out anyway. A conical spot core which spots the drill will speed up the drilling operation. Aluminum- or brass-alloy internal threads are seldom cast, because the large shrinkage of these metals may result in galling as the stud core is removed.

External threads may be made by a threaded collar which must be unscrewed. More frequently they are made by a split section die, because of the faster production. A small fin is left where the split or parting is made, so that the thread must be die chased if a close fit with a mating part is required.

The Whitworth form of thread, which has rounded root and crest, is the easiest to die cast and is often used with another die-cast Whitworth thread. But where the die-cast thread must mate with a machined thread, the United States standard form is used because the

Bad   Good

Bad   Good

Fig. 15.25. Design changes to avoid undercuts.

machining is much enhanced. Square threads may be die cast, but require complicated coring because of the undercutting. Tapered pipe threads are readily die cast, although for a tight, accurate joint they are usually chased with a cutting die. Many die-cast threads are used as cast, except for fin removal, where exceptional accuracy is not required. Shrinkage of the piece causes an error in pitch but this is not limiting unless the thread is unusually long.

Inserts. Die castings and also cold-chamber pressure castings sometimes employ cast-in inserts of dissimilar metals, or nonmetallic elements, to impart locally to the casting certain properties which the cast alloy itself does not possess. These properties may include higher strength, greater hardness and wear resistance, special electric or magnetic paths, or superior bearing qualities. The inserts are placed in the die before the casting is made and must be securely positioned. Since they are usually placed in the hot die by hand, their use lengthens the cycle and reduces the production rate; therefore, they can be used only when the increased cost is justified by the benefit obtained. The most common insert is a screw-machine product of steel or brass, but stampings, forgings, and even sand-cast or die-cast inserts have been used to advantage. When using inserts of metal other than that of the casting itself, the possibility of galvanic corrosion should be considered.

Inserts are usually undercut, knurled on the surface, or provided with projections or holes which anchor them securely when metal is cast around them. These provisions also prevent the insert from turning or pulling from the casting. When plated inserts are to be used in zinc castings, they should never be tin- or cadmium-plated, as such plates would seriously affect the chemical stability of the casting.

Bearing inserts may be of almost any metal, such as graphited bronze, porous bronze (porous-bronze inserts should not be oil filled until after the casting has been made), hardened steel, or even wood or a molded phenolic when used with zinc alloy. The molten zinc entering the mold solidifies quickly and barely discolors the surface of the wood. Hardened steel inserts may be cast-in without losing their tempered hardness. Bearings and bushings, if accurately machined before insertion, require little or no machining after casting in place, as they can be positioned quite accurately on cores or fixed pins. At most, only a little reaming of the bore should be required after casting. Some die-casting alloys and cold-chamber pressure alloys, especially zinc base, have good bearing qualities, and so they

do not always require a bushing insert for a bearing (see Chapter 8).

Gears. Any type of gear with a tooth form that will clear a die can be die cast or cold-chamber pressure cast. Although the majority of gears cast by these processes are for light mechanisms, some for quite heavy service have been made. For light lathe applications, with gears running dry, greater wear resistance has been attained with die-cast zinc-alloy spur gears than with gray cast-iron machined gears.

Die-cast and cold-chamber pressure-cast spur and internal gear teeth, in general, have to be given a slight draft, at least if the face width is considerable; hence the tooth elements are not exactly parallel unless a shaving or equivalent machining operation is performed. Some other forms of teeth, such as those for bevel gears, are die cast or cold-chamber pressure cast with substantially perfect tooth form without machining. Internal gears are as easily die cast or cold-chamber pressure cast as those of the external or spur type. Both may have teeth shrouded on one side with resultant strengthening, whereas cut gears of this type are difficult and expensive to machine (see Fig. 15.26). It is also an easy matter to die cast or cold-chamber pressure cast a square or splined hole in the hub or to split the hub for clamping to a shaft, whereas it would cost much more to obtain similar results by any other process.

FIG. 15.26. External-pressure casting with internal gear teeth and shrouded, toothed hub.

Worms and worm wheels are readily cast by either the die or cold-chamber pressure methods. However, for precision gears of this type on which very smooth tooth surfaces are required, some machine work is necessary, and allowance for this must be made in the casting.

Tolerances. The tolerances and draft allowances required on metal-mold castings made from different materials and by different casting methods are shown in Table 15.1. Also shown are the minimum wall thickness and hole dimensions that can be produced in each case. This table should be studied carefully before assigning dimensions to a design and, wherever possible, larger allowances than those given

should be used. It is sometimes possible to cast to even closer tolerances or smaller size, but the die caster should be consulted on such designs before they are settled. Fig. 15.27 is an example of a die casting made with a relatively thin section.

Finished Surfaces. Parts can be plated most inexpensively and for best appearance and protection if the following conditions can be observed in the design.

(1) Avoid deep, narrow, closely spaced ribs. They entrap buffing compound, are difficult to clean properly, and are hard to plate since the front faces absorb most of the plating current.

FIG. 15.27. Thin die-cast radiator ornament.

(2) Recesses in which gas can be entrapped should also be eliminated. These areas will not be plated and the flow of excess gas over the surrounding surfaces may cause peeling and poor appearance.

(3) Generous radii in re-entrant angles avoid the necessity for applying excessive thickness of plate to assure meeting minimum coating requirements in these areas.

(4) Sharp outside corners and points should not be included in the design, because deposits on such areas tend to be rough and brittle.

(5) Large concave areas are difficult to plate because of low current density at the center. Convex shapes are easier to plate than flat shapes.

(6) Since a plated part usually must be buffed, a brilliant luster cannot be obtained in those areas which the buffing wheel cannot reach.

Die and cold-chamber pressure castings are supplied with a commercial surface finish unless otherwise specified. This finish is the best obtainable in regular routine with modern machinery and with up-to-date and carefully controlled metallurgical and casting prac-

Table 15.1   Tolerances for Metal-Mold Castings

[These data should be used for general guidance only. Actual design conditions will affect possible minima or maxima.]

Manufacturing Method	Metal	Tolerances within Solid Die, in in. per in.	Minimum Wall Thickness, in in. *	Minimum Hole—Dimensions		Minimum Draft per Side per Inch of Depth of Side Wall or Holes, in. per in.
				Maximum Diameter, in in.	Maximum Depth, by diam	
	Metal	Remarks Tolerances should be as liberal as possible in the interest of low die and casting costs. Wherever permissible they should be greater than those given below. Still closer limits than those given are obtainable, but only at higher costs. Tolerances affected by moving members must be somewhat greater (across parting lines, etc.).	Remarks Varies with alloys. (Aluminum-silicon alloys, for instance, will cast in thinner sections than aluminum-copper alloys.)	Remarks Cores for casting holes produce a beneficial chilling effect. Therefore, where possible, all holes should be cored, except when so small or deep that cores may be warped or bent under the shrinkage stresses of the freezing metal, or when drilling or punching is cheaper.		Remarks Draft per side on walls where metal shrinks away from die could be somewhat smaller. Liberal draft results in superior surface finish.
Die and cold-chamber casting	Magnesium alloys	±0.0015, but at least ±0.003	0.030 for small sections. More for larger sections	Smaller than 3⁄32 3⁄32 to 1⁄4 1⁄4 to 1	Not cored 3 times 3 to 5 times	0.010
	Aluminum alloys	±0.0015, but at least ±0.003	0.035 for small sections. More for larger sections	Smaller than 3⁄32 3⁄32 to 1⁄4 1⁄4 to 1	Not cored 3 times 3 to 6 times	0.010

Process	Alloy	Tolerance	Minimum wall section	Section size	Cores	
Die and cold-chamber casting	Zinc alloys	±0.001, but at least ±0.0025	0.020 for small sections. More for larger sections.	Smaller than 3/32 / 3/32 to 1/4 / 1/4 to 1	Generally not cored / 3 to 8 times / 6 to 8 times	0.005
	Brass and bronze	±0.003, but at least ±0.005	0.050 for small sections. More for larger sections.	Smaller than 3/16 / 3/16 to 1/4 / 1/4 to 1	Not cored / 2 times / 2 to 4 times	0.015
Permanent-mold casting	Magnesium alloys	±0.0015, but at least ±0.010	0.1875 (regardless of whether surface is rough or smooth)	Smaller than 1/4 / 1/4 to 1/2 / 1/2 to 1	Generally not cored / 3 times / 3 to 6 times	0.015
	Aluminum alloys	±0.0015, but at least ±0.010	0.125 (0.090 where at least one side can be reasonably rough)	Smaller than 1/4 / 1/4 / 1/4 to 1	Generally not cored / 3 times / 3 to 6 times	0.015
Bronze		±0.005, but at least ±0.010	0.075 for small sections. More for larger castings	Smaller than 1/4 / 1/4 to 1/2 / 1/2 to 1	Generally not cored / 2 times / 2 to 4 times	0.020
Plaster-of-Paris casting	Brass and bronze	±0.003, but at least ±0.005	0.032 for small sections. More for larger areas	Smaller than 1/8 / 1/8 to 1/2 / 1/2 to 1	Generally not cored / 3 times / 3 to 6 times	0.010

* The minimum wall section that can be cast with different alloys and by different processes is not absolutely fixed. It depends on the size and design of the casting, on the location of the section with reference to heavier adjacent sections, on the die, the alloy, type of machine, and the pressure applied. In general, the lower the melting point and the more fluid the metal, and the shorter the distance the metal must flow between the chilling walls of the die or mold, or the faster it traverses the distance, the thinner the wall may be. There is practically no limitation on casting heavy wall thicknesses as may be encountered in commercial applications. Sections somewhat heavier than minimum castable are recommended (especially for die and pressure castings) when castings are to be plated, as they hold greater promise for smooth surface.

FINISHES: Metal-mold castings can be finished with three different finishes, as follows, and should be marked on drawings to designate type of finish desired.

No marking—Commercial: Standard finish produced by commercial, but carefully controlled, routine.

Decorative: (Required for plating.) Free from flow marks and from swirls and other surface imperfections.

Poorer than commercial: suitable for unexposed or painted surfaces.

tices. Such a finish is reasonably free from surface imperfections, such as pits, draws, run marks, and scabs.

Where a better finish is required, it must be requested of the die caster. Such a finish naturally costs more than the commercial finish. When castings are used in locations where the surface appearance is of no importance, even the commercial finish would not be needed and a subcommercial finish would save some cost.

Large flat surfaces are difficult to make exactly flat, and when polished the irregularities will be shown by reflected light. For that
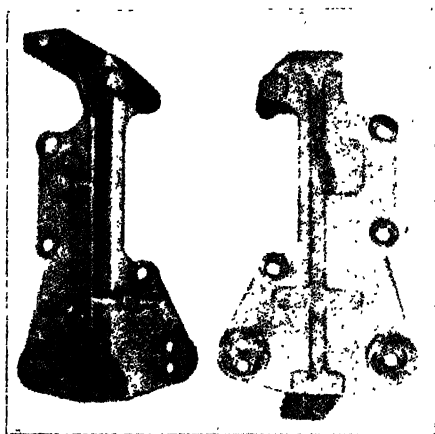
FIG. 15.28. Top and bottom views of a casting, showing rib (left) and shadow bead (right).

reason large surfaces are frequently given a slight curvature, or are finished with beads, trimming, etc., to break up the large flat area. When heavy ribs are used under a surface, the beading should be opposite the ribbing to eliminate the possibility of shadow marks occurring because of slight indentation of the metal when the rib cools. Fig. 15.28 shows a bead used to avoid a shadow mark.

The scope of metal-mold castings, particularly of die, cold-chamber pressure, and permanent-mold castings, can be enlarged materially through combination with other manufacturing processes, such as cold forming and punching. Fig. 15.29 shows a die-cast pull knob for a refrigerator vegetable drawer, cast with a straight skirt which is afterwards cold formed into spherical shape. Hollow-box sections are frequently cast as an open U and afterwards transformed into a closed box by bending part of the U over at right angles. When other separate parts are to be riveted to die castings, pins are sometimes
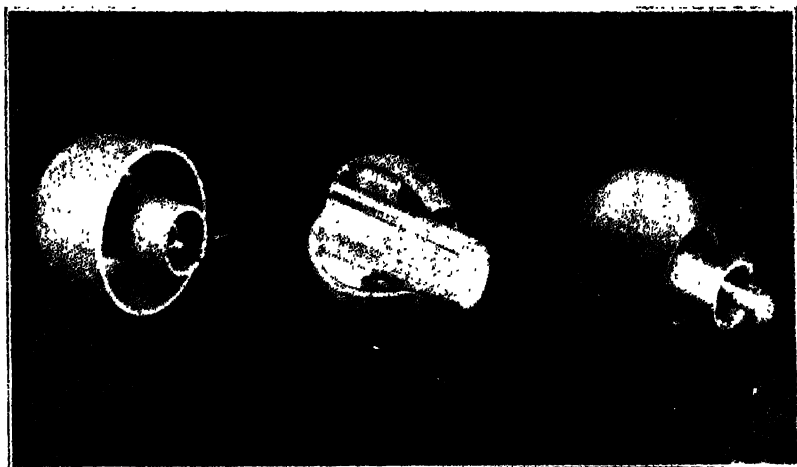
Fig. 15.29. Doorknob made by die casting and subsequent cold forming of the skirt.
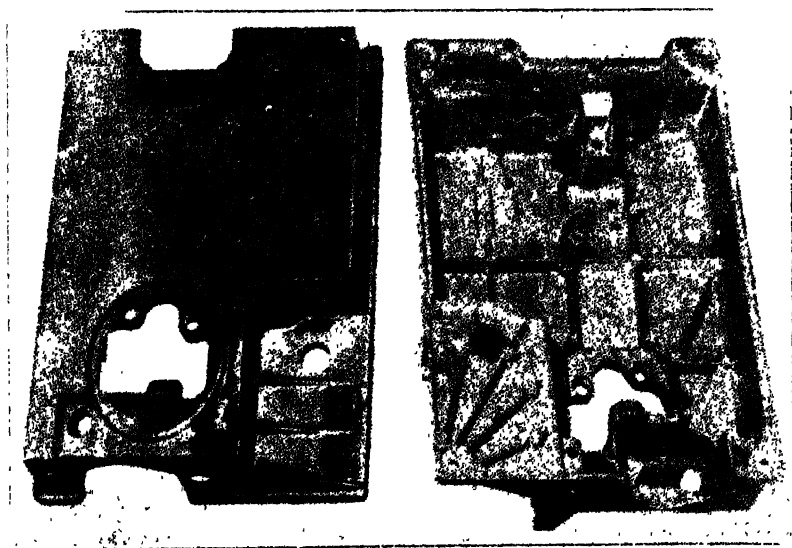
Fig. 15.30. Two views of die-cast sewing-machine base, showing complexity, use of ribbing, etc.

cast integrally with the die casting proper, and riveted over after assembly. Such cold-forming operations are usually performed on zinc die castings, although aluminum alloys now available lend themselves to the same process.
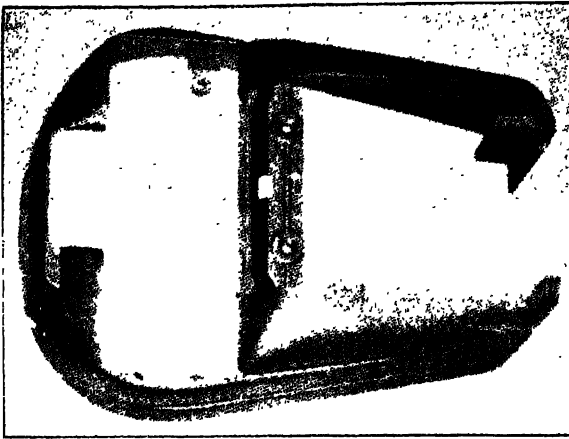
Fig. 15.31.   Cold-chamber pressure casting of magnesium alloy for business-machine housing. Note thin sections and fine surface finish.

15.32   CENTRIFUGAL CASTINGS

The centrifugal casting process consists in pouring molten metal into a dry-sand-lined mold or a permanent metal mold which is revolving at a speed ranging from 600 to 3000 rpm, depending upon the diameter of the casting and the alloy to be used. The centrifugal action forces the molten metal tightly against the mold with much higher pressure than is obtained in sand casting. Greater detail is obtained in the casting surface, and the structure of the solid casting is dense. Castings of symmetrical shape are especially suited to this method, but many other types are produced to take advantage of its characteristics.

There are three variations to this casting process. The designations usually used for them are true centrifugal, semicentrifugal, and centrifuging.

True centrifugal casting is used for producing thin- or thick-walled hollow cylinders with a bore concentric with the outside. Casting machines for long lengths, such as pipe, consist of motor-driven rollers to rotate the mold about a horizontal axis. Sand lining for the mold is provided for iron or steel castings. The metal is poured after

the mold is up to speed, and no core is needed to provide a true cylindrical inside cavity. For short parts, such as aircraft-engine cylinders, the mold is fastened to an end plate and rotated either horizontally or vertically. When the mold is rotated about a vertical axis, however, theoretically a paraboloid will result because of the effect of the gravitational force. Slightly concave or convex sections can therefore be obtained by proper control of speeds, but at the higher speeds this effect becomes increasingly smaller and the bore will be essentially straight.

Although the free internal surface produced by these methods will always be a surface of revolution, the outer surface may be hexagonal, square, octagonal, or round, etc., with or without flanges or grooves. Occasional bosses or protuberances breaking the symmetry of the perimeter may also be cast, provided they are not too high or too thin. Flanges, bosses, etc., should not be much thicker than the wall of the cylinder so that internal stress resulting from unequal cooling will not be excessive. It is not good practice to attempt to cast centrifugally two flanges on opposite ends of a long tube, because during cooling both would act as an anchor and prevent normal shrinkage of the casting.

Refractory cores are used in this process for the purpose of producing irregularly shaped inside walls. In the majority of instances, however, the inside of the casting is machined to remove the impurities that gather there. These impurities include slag, oxides, pieces of refractory, etc., which are lighter than the metal, and are squeezed out of the rotating mass to the inside under the influence of the greater centrifugal force on the heavier metal.

In *semicentrifugal casting* the mold, usually a stacking of several flat sand or die molds, is rotated about a vertical axis. The speeds utilized relative to the stacking height result in a solid center for the cast parts. Dense structure is produced at the exterior, and poorer metal occurs at the center, where it may have less required properties or may be machined out.

The *centrifuge* method of casting utilizes the centrifugal force of rotating the mold about a vertical axis to feed molten metal from a central sprue through radial gates to several cavities located around the outer portion of the mold. Irregular shapes may be produced but sizes are limited by the size of centrifuging equipment.

The elimination of drossy metal from the body of the casting is only one of the metallurgical benefits of these processes. Others are finer grain size, slightly increased density, uniform distribution of

alloying elements, and elimination of the internal centerline weakness caused at the boundary of two separate columnar growths which occur when a casting is cooled simultaneously from two sides. These factors account for as much as 20 per cent increase in the strength of parts centrifugally cast compared with still castings. Elongation and hardness will also show an increase.

Other advantages of the process are the low cost of molds, high metal yields, the applicability to large, long, hollow shapes, and the casting of any metals, especially those difficult to work by forging. Monel, stainless steel, and beryllium copper are cast, in addition to copper, aluminum, iron, and steel alloys.

The limitations of the centrifugal casting process are:

(1) Castings located concentric to the axis of rotation must have a through hole, and extra metal must be provided for machining on the inside of this hole when impurities are present in the metal.

(2) Because of the comparatively high speeds of rotation and the large masses ordinarily cast, the parts should be dynamically balanced. Although small amounts of unbalance are sometimes tolerable such as, for example, small ports in cylinder liners, any considerable unbalance will overload the bearings and structural members of the casting machinery. Hence, when fairly large holes are required in the casting in such a location that they would contribute to the dynamic unbalance of the part, they are machined afterward, the part being cast solid.

(3) Close tolerances and sharp outlines are obtainable only at the periphery. In castings located eccentric to the axis of rotation of the mold, the outlines near the center of rotation will not be as sharp as those at the outer circle. Finish allowances should be approximately $\frac{1}{16}$ in. per in. diameter with $\frac{1}{8}$ in. minimum on the outside diameter and $\frac{1}{8}$ to $\frac{1}{4}$ in. allowance for the inside diameter. Minimum wall thickness is about $\frac{1}{4}$ in.

Typical applications include gun shells, gear blanks (grain especially good), long steel cylinders, pipes, pressure vessels, piston rings of small eccentricity, bushings, Babbitt liners, squirrel-cage rotors of small induction motors, and other similar articles in nearly any castable metal.

15.33 CHOICE OF METAL-MOLD CASTING PROCESS

The final selection of the metal-mold casting process, in competition with sand casting or any other method of manufacture, will depend on the best balanced combination of (a) suitability of the ma-

terial under consideration and physical characteristics imparted to it by the process; (b) competitive and advertising advantages through the use of the process; (c) cost of tools and of each piece in a finished state, inclusive of all machining; (d) total saving in cost of all finished pieces during the period allowed for the liquidation of tools.

The physical properties imparted by the various casting processes have been summarized in Table 15.2. This table should be of value

Table 15.2   Relative Characteristics of Different Casting Methods

(Numbered in order of preference)

Casting Process	Sand	Plaster of Paris	Permanent Mold	External Pressure		Centrifugal (In Metal Molds)
				Die	Cold Chamber	
Materials suitable for process	All casting metals	Yellow brass, bronzes, Zn, Pb, Sn	Al alloys, bronzes, iron, Zn + Pb	Zn alloys (containing Al), Al alloys, Pb + Sn	Al alloys, brass, bronze, Mg alloys, Zn alloys (no Al)	Al alloys, brass, bronze, Monel, iron, and steel
Porosity	6	2	3 *	5	4	1 †
Surface smoothness	6	1	4 *	2	3	5 *
Sharpness of casting outline; dimensional tolerances	6	1	4 *	3	2	5 *
Strength (solid metal)	5	6	3	2	1	4 †
Thinness of section	5	1	4	3	2	6 (as cast)
Tool cost (pattern and molds) ‡	1	3	4	5	6	2

Speed of production and labor cost per casting ‡	On basis of most economical tool setup (as to number of impressions on one pattern plate or in one die) for comparative production quantities.					
	For small and moderate production inclusive of setting up of die:					
	1	2	4	5	6	3
	For large production					
	6	5	3	1	2	4
Possible savings for machining	5	1	4	3	2	6

* Only in material next to metal mold.
† In metal left after removal of drossy material from inside of wall; outside outline = 3.
‡ Tool cost and cost per casting depend on number of patterns per plate or impressions in die; the more castings can be made at one operation, the lower the labor cost per piece, with inversely increasing tool cost. Sand and plaster-of-Paris patterns lend themselves more economically to multi-impressions than metal molds.

to the engineer in estimating suitability of both material and process. The numbers given are in order of preference (1 being best, 2 next

best, and so on) and are self-explanatory except for the qualitative indication of strength of material. This property should be considered in conjunction with data on porosity in the same table. For instance, a cold-chamber pressure casting of a material of relatively low unit strength may have higher actual strength and certainly will be more dependable than a die casting of a material of somewhat higher unit strength, if there is the possibility of internal porosity in the casting.

Metal-mold castings have higher strength, better surface appearance, and closer tolerances than sand castings of the same metal, but they entail higher tool cost. Owing to the close tolerances and good surface of metal-mold castings, they usually obviate costly machining operations necessary with sand castings, except for very close tolerances. They frequently cost less than forgings requiring considerable machining, or drawn parts necessitating more than one anneal between draws, or even screw machine parts where much of the material is lost in machining.

The question of plastics vs. metal-mold castings cannot be covered in detail here, but the following general statements will aid in evaluating the metal-mold castings.

Die castings and cold-chamber pressure castings have the following advantages:

(*a*) Higher strength (tensile, compression, bending, impact, and creep).

(*b*) Higher temperature resistance.

(*c*) Greater electrical and heat conductivity.

(*d*) Better dimensional accuracy.

(*e*) Lower die cost (original and maintenance).

(*f*) Higher rate of production.

(*g*) Larger variations in section thickness possible.

Plastics have these advantages:

(*a*) Less weight (except magnesium castings).

(*b*) Better smoothness and appearance of surface.

(*c*) Color, gloss, transparent and translucent effects.

(*d*) Electrical insulating properties.

(*e*) General corrosion resistance.

Metal-mold castings should be considered wherever production is high or even moderately high (in one case, zinc die castings with a yearly production of 150 have cost less than machined gray iron castings), and where the mechanical requirements are not beyond the possibilities of this type of casting.

The length of time allowed for liquidation of tools—that is, for cancellation of the tool cost out of the savings effected in the manufacture of the finished part—varies with the job. If the order is not likely to be repeated, the period should be the life of the order. For a standard part, the period should depend on the prospective life of the design and on the engineering and advertising advantages derived from the use of the process.

Even after the economic and mechanical advantages of one or another form of metal mold process have been definitely established, the designer should make sure that the design is definitely settled and not subject to early change due to shifting sales sentiment or to service troubles. The heavy investment in mold cost is likely to militate against an otherwise highly desirable change, or at least to load the development account unduly. The design should be laid out for the selected form of metal mold, but if there is any uncertainty about the stability of the design, it is advisable to handle production during the introductory period with sand castings or in some other less restricting form.

Metal-mold casting has been in commercial existence since only about 1910, but great possibilities have been indicated and great developmental strides have been taken. Undoubtedly, there will be new advances rendering obsolete some of the methods presented in this chapter. One development that may prove of immense future importance is adaption of vacuum technique to the conventional processes, with possibility of greater purity, higher strength, and higher leak proofness. Yet these methods of production have reached a position of importance in manufacturing which may be expected to continue.

Review Questions

1. The following terms are used in reference to sand molds. Describe the part to which they refer. (a) Cope, (b) drag, (c) cheek, (d) sprue, (e) gate, (f) riser, and (g) core.

2. Name and describe the three classes of molding operations. What is the main difference between them? What type of equipment is used with each?

3. What is the difference between dry-sand molds and green-sand molds? What are some of the advantages and disadvantages of each? Why is "skin drying" employed with some green-sand molds?

4. Name some of the factors which favor making a pattern of wood instead of metal. What advantage is gained through the use of a match-plate pattern instead of a single (split) loose pattern?

5. Who is normally responsible for choosing the type of pattern and its design? Explain why the designer should indicate locating points on the

drawing. What type of partings are preferred? How will the patternmaker normally add draft to the pattern if no engineering instructions are given?

6. Three pieces of a simple casting requiring no cores or loose pieces are to be made in sand. What pattern would be recommended? What pattern for 100 pieces? What pattern for 5000 pieces?

7. What three main characteristics of solidifying metal have an important influence on the soundness of castings? Name the two kinds of defects attributable to poor design.

8. Hot tears can be prevented by eliminating hot spots and stresses, particularly concentrated stresses. Name and explain three design rules which accomplish these purposes. How can contraction cavities be prevented?

9. What is directional solidification? How may it be controlled to produce sound castings?

10. How may the soundness of a finished casting be tested without destroying the casting? What two methods are used to detect surface cracks?

11. How do the strength, surface finish, accuracy, and tool cost of plaster-of-Paris castings compare with sand castings? With metal-mold castings?

12. What is the "lost-wax" process? Name two industrial applications for this process.

13. Name the four classifications of metal molds. How do permanent molds differ from semipermanent molds? How do the castings made by each process compare? What are slush castings and what characteristics do these castings possess?

14. In what way does the die-casting process differ from cold-pressure casting? Describe the two types of die-casting machines in common use. Name the metals and alloys cast in each type of machine and explain why they are so cast. What characteristics do die castings and cold-pressure castings have in common? Why may some die castings (and, to a lesser extent, cold-pressure castings as well) blister when heat treated?

15. What contributes to shrink holes in die castings? What rule of design should be followed to avoid shrink holes?

16. State the differences between true centrifugal casting, semicentrifugal casting, and centrifuging. Which method is used for cast-iron pipe? What are the advantages of the true centrifugal process? What influence has the average rotational speed upon centrifugal casting, and what limits the speeds used?

17. Compare metal-mold castings, as a class, with sand and plaster-of-Paris castings, and describe the design conditions under which they are most favorable.

16 POWDER METALLURGY

16.1 INTRODUCTION

The powder metallurgy process dates back to 3000 B.C., when the Egyptians utilized something of its technique for making implements and weapons. They produced a sponge iron by reducing iron oxide with charcoal, and then hammered this iron into shape. Through the years the art progressed but little until the classical experiments of W. H. Wollaston early in the nineteenth century resulted in production of solid platinum. Wollaston's work formed the first scientific approach and set the stage for the many improvements that were achieved in the first half of the twentieth century.

The process represents an important method of producing metallic parts from powders of a single metal, of several metals, or of a combination of metals and nonmetals. It consists of the successive processes of mixing the powders mechanically, compacting them at high pressures into a preliminary shape, and heating them at elevated temperatures, but below the melting point of the major constituent. Diffusion causes the particles to unite into a single, strong, smooth metallic part much like the same composition produced by melting the various constituents together.

16.2 METAL POWDERS

The characteristics of powders used are closely related to the properties of finished powder metallurgy parts. The powder-production processes are therefore controlled so as to regulate the particle shape, size, size distribution, and purity. The particle shape is largely inherent with the process. For instance, sponge or porous particles are produced by the reduction method and spherical particles by the carbonyl method. All these properties of the powder affect flowability and compacting characteristics and must be closely controlled if smooth, trouble-free operation is to exist in the production of the final parts.

The methods currently employed for production of metal powders are: (a) reduction of powdered metal oxides by contact with carbon or hydrogen atmospheres at temperatures below the melting point of the metal (for tungsten, iron, cobalt, nickel, and molybdenum); (b) electrolytic deposition at high current densities and subsequent mill grinding (used for copper, iron, tantalum, silver, and some other metals); (c) condensation of metallic vapors to a powder, as in the carbonyl process (for iron, nickel, and the lower melting point metals); (d) atomizing to a powder by entraining liquid metal in an air jet, or melting and atomizing metal wire by high-velocity burning gases, as in the Schoop process; (e) mill grinding of cast pellets or shot produced by pouring molten metal through a sieve into water; (f) stirring during solidification, called *granulation;* and (g) stamping.

The various powders are weighed in the correct proportions and mixed, wet or dry, in a ball mill. Wet mixing with water or some organic solvent is employed to insure better mixing, prevent explosions, prevent surface oxidation, and keep dust to a minimum. Die lubricants are often added to facilitate the pressing operation which follows.

Mixing or blending is still employed even when using pre-alloyed powders. It results in uniformity of particle size and shape throughout a large amount of powder and insures better control of subsequent pressing and sintering operations.

16.3   BRIQUETTING

After the required amount of metal powder has been mixed and placed in the die, a plunger compresses the powder under pressures of about 30 or 40 tons per sq in. with a compression ratio (loose filled volume to compressed volume) ranging from 2:1 to 6:1. This operation is known as "briquetting," because the powder is squeezed together into a briquette. Particle shape and size distribution must be taken into consideration by the manufacturer. Speed of pressing, die wear, etc., naturally limit the pressures which can be used economically, but the density is not necessarily increased as the pressures exceed 30 or 40 tons per sq in.

16.4   PRESINTERING AND MACHINING

This is a low-temperature, short-time sintering operation in which the pressing lubricant volatilizes and some strength is attained in the part. If much machining is required, it is done after presinter-

ing, while the part is relatively easy to machine. If machining is not required, or not to a great extent, presintering is eliminated.

16.5 SINTERING

In sintering the briquette, it is heated in a furnace at a point below the melting point of the major constituent; sometimes a component with a lower melting point will become liquid. During the sintering process bonding of the individual powder particles takes place in any of three ways: (1) melting of a minor constituent, (2) diffusion, (3) mechanical bonding or entrapment of nonmetal particles within a diffused metal matrix. Atmospheric control is necessary to prevent oxidation. Pure dry hydrogen, cracked ammonia, inert gas, or cracked city or natural gas are used, according to the material being sintered. The former atmosphere is absolutely necessary when sintering Alnico and stainless steel. The latter is the cheapest and most widely used.

Shrinkage may occur in sintering. This is increased by higher temperatures and lower briquetting pressures, and varies with the metal. As a result, the tolerances of sintered parts are generally on the order of ± 0.001 in. per in. in the plane perpendicular to the direction of pressing and about ± 0.005 in. in the direction of pressing.

16.6 OTHER OPERATIONS

Hot or cold repressing operations, called "coining" and "sizing," may be used to produce higher strengths and especially closer tolerances in sintered parts.

For parts requiring self-lubrication suited usually to intermittent light-load duty, oil may be introduced into the pores of the sintered part. This may be accomplished by simple immersion of small parts, but larger parts may require vacuum-pressure cycle treatment.

Recent progress has made possible substantial increase in strength and density by impregnating, or *infiltrating,* molten metal into the pores of the sintered part. Since the temperatures involved are themselves in the sintering range, the compact is usually given only a mild sintering operation before impregnation. Coining or sizing operations, if desired, are performed afterwards.

To reduce the pressures needed in briquetting and to help eliminate uneven sintering shrinkage, heating of the dies or the part has been attempted to make the powders somewhat plastic during pressing. It was hoped that superior strength, hardness, and impact

properties might be obtained and that the normal briquetting and sintering operations could be incorporated into one. So far, except for special cases, economic considerations and great technical difficulties have discouraged use of this technique.

16.7 STRUCTURAL-PRODUCT APPLICATIONS

Successful use of powder metallurgy for producing structural parts in competition with other methods of production requires on the part of the designer an appreciation of the advantages and disadvantages of the powder metallurgy method. Such an appreciation will guide the designer to incorporate as many of the advantages and as few of the disadvantages as possible. Some of the important advantages of the process are as follows.

ADVANTAGES   (1) *Elimination of Scrap.* Only the required amount of material is involved throughout the entire manufacturing process. By other methods the scrap may run as high as 70 per cent.

(2) *Elimination of Machining Operations.* After the part comes from the heating, or sintering, process, the tolerances are close enough that the part may be used as is or with a sizing operation for most applications. Thus, such difficult machining operations as slotting a square hole or finishing a sunken surface are avoided. The dimensions are accurate, the edges are sharp, and the surfaces are smooth.

(3) *Suitability to Mass Production.* The pressing, or briquetting, operation consists of but one stroke of a press at a speed of up to 60 strokes per min, and the sintering operation can process many hundreds of parts in one heat. The temperature required is less than the temperature for casting. Thus, high-quantity production is relatively easy, the time per part is short, and labor costs are low.

(4) *Better Control of Composition and Structure.* The nature of the process insures that the exact desired proportions and purity of the various metal powders in the finished product can be consistently reproduced in a uniformity of composition and structure unapproachable by foundry methods. Also, the sintering atmosphere can be accurately controlled. In this way the product can be kept under more exact control.

(5) *Production of "Impossible" Parts.* Parts with controlled porosity, parts made from a mixture of metals and nonmetals, and parts of highly refractory metals can be made through the powder metallurgical process (see 16.8).
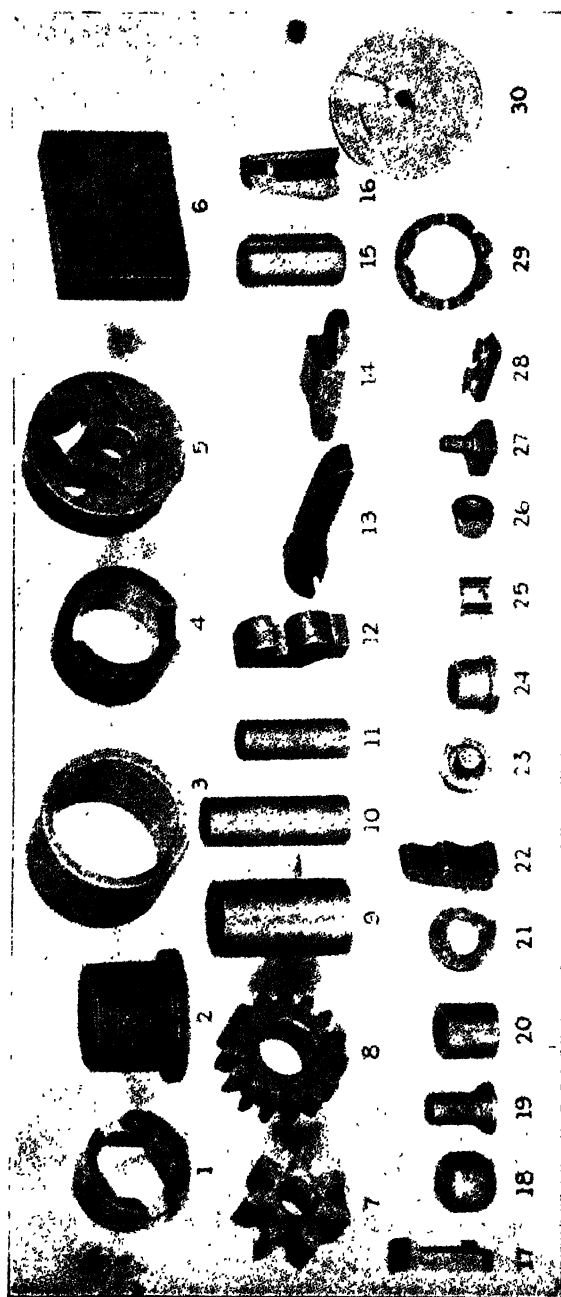
Fig. 16.1. Miscellaneous parts made from pressed powders. (View approximately 40 per cent actual size.)

1, 3, 9, 10, 11, 18, 19, 20, and 24. Bronze bearings and bushings of the self-lubricating type.

2 and 4. Self-lubricating bushings made from iron powders.

5 and 7. Automotive oil-pump iron parts.

6. Block composed of alternate layers of compressed iron and bronze.

8. Self-lubricating iron gear used in an electric washer.

12, 21, 23, 25, 27, and 30. Miscellaneous parts made from mixtures of copper and tin powders.

13, 14, 16, 17, and 22. Iron dovetails and brackets, chiefly automotive.

15. Self-lubricating spline bearing made from iron powder.

26. Porous-bronze cone used as an oil filter, to replace one of ceramic materials.

28. Cutter for G. E. Disposall unit. Made of Carboloy powder.

29. Bronze bearing race.

DISADVANTAGES There are several disadvantages inherent in the powder metallurgy process. Although some may be reduced by future research, they must be considered limiting at present.

(1) *High Cost of Dies.* Since pressures of the order of 30 tons per sq in. are used for briquetting, the wear on the dies is high, and large, powerful, expensive presses are required. The original costs of dies are comparable with mold costs for plastics. Accordingly, when parts can be made by other methods, powder metallurgy is usually not considered unless orders in the neighborhood of 10,000 parts are anticipated.

(2) *Lower Physical Properties.* The inherent porosity in powder metallurgy parts results in lower tensile and yield strengths, lower elongations, and much lower impact values. With small indentors and light loads which eliminate porosity effects, local hardness values compare well with wrought materials.

(3) *Higher Cost of Raw Materials.* The cost of metal powders suitable for present-day products made by this process is several times that of metal used for making wrought material. Often, however, powder raw material is more readily available since steel scrap or other by-products from metal working operations are a satisfactory source of metal powders. The cost of manufacturing powders is steadily being reduced by research, experience, and higher quantity production.

(4) *Limitation on Design of Part.* The area of the piece directly determines the required size of press. Few manufacturers have available automatic high-speed presses having over 80 tons capacity. If pressures of 30 tons per sq in. are used, the size of part is thus limited to less than 3 sq in. of cross section normal to the direction of pressing.

Powders when pressed do not flow around corners as do plastic materials, nor do they transmit pressures like a liquid. Because of this, the design of the part being formed is very important, especially when high briquetting pressures are used. A cast part, in order to be made by powder metallurgy, is likely to require redesign. The design features will be discussed at the end of the chapter.

16.8 SPECIAL PRODUCT APPLICATIONS

The powder metallurgy process permits manufacture of parts that would be impracticable or even impossible by any other method. Such industrial applications are probably the better known because

of the myriad of uses and tradenames that have become prominent. Some of the more important of these are:

(1) *Ductile Tungsten.* The very high melting point of tungsten prevents it from being melted and cast as can iron or steel. Dr. W. D. Coolidge * developed a process whereby he pressed, sintered, and resintered tungsten powder gained from a reduction of tungstic oxide in hydrogen. The resulting bars could then be swaged and drawn through diamond dies to form a strong, ductile wire 0.001 in. in diameter and smaller, which is used as the filament in incandescent lamps. Molybdenum, tantalum, and columbium can be similarly processed. A number of applications have been made of tungsten parts (e.g., Hevimet) where the high density is of advantage to providing mass or inertia in a limited space.

(2) *Self-Lubricating Bearings.* These are made from iron powders, mixtures of copper and tin powder, and of iron and copper powders, all with or without graphite. Fine interconnected pores constituting 25–30 per cent of the volume are produced in the sintered compact by admixture of certain nonmetallic elements that volatilize in sintering, or by adjusting pressure and sintering temperature. Impregnation with oil after pressing and sintering furnishes a constant supply of lubricant to the surface by capillary action. This type of bearing finds application where lubrication is not possible after assembly or where oil splash is undesirable. If closer tolerances are needed than result in the sintered product, ball or punch burnishing is used for sizing. Machining has the tendency to close the pores, particularly in copper-base bearings. It is possible to carburize and heat treat an iron-base bearing of this kind and thereby produce a wear-resistant, self-lubricating surface. Applications include self-lubricating parts for oil-pump gears, door catches, cams, washers, bearings, guide blocks for machine saws, and many other articles.

(3) *Contacts and Electrodes.* Electrical contacts and resistance-welding electrodes are made by the process, combining the high conductivity of copper or silver with the resistance to fusion at high arcing temperature of such metals as tungsten, molybdenum, and nickel.

(4) *Permanent Magnets.* Low-cost permanent magnets of aluminum, nickel, cobalt, and iron (see Chapter 6) are made in small intricate designs. These magnets, unlike porous bearings and the like, are made to about 97 per cent of full density and are finer

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* Former director of the General Electric Research Laboratory.

grained, stronger, and more homogeneous (making for more magnetic uniformity) than the same parts cast.

(5) *Cemented Carbides.* Carboloy, Kennametal, and similar cutting tools suited to high-speed machining of cast iron, Bakelite, hard rubber, and other materials that cause rapid wear on steel tools are made by this process. Usually they are prepared as small components that are copper brazed to the desired tool shank. Tool bits, drills, high-production die sets, and production plug gages are other applications for powder metallurgy parts of this type. Preliminary sintering is often employed, since the compact acts like a hard gray chalk in this condition and can be easily cut and shaped to the desired size. Full hardness is developed in the final sintering during which the part shrinks about 20 per cent.

(6) *Friction Materials.* Fine copper-base metal powder mixtures (copper, tin, silica, graphite, lead) can be pressed into thin wafers (as thin as 0.012 in.) and bonded during the sintering operation to a copper-plated steel backing member. These thin friction surfaces are used running against steel mating surfaces in disc-type clutches and brakes, particularly for aircraft landing gear.

The advantages of the material are high heat conductivity, controllable friction properties (by controlling the mix), and the possibility of saving space by the use of thin layers.

(7) *Generator Brushes.* Copper and graphite powders are sintered together to make current-carrying brushes that combine the high conductivity of copper with the light weight and lubricating properties of graphite. These brushes can be pressed from flake copper so that they show a laminated structure with quite low resistance in the direction parallel to the laminations.

(8) *Filters.* By controlling particle size of globular powders and their pressing and sintering technique, parts can be made to have up to 50 per cent porosity. This porous metal product has found application where its functions have been to break up a main flow of material into small streams, to remove undesirable materials from liquids or gases, to isolate a flame or fire in a chamber or line, and to remove one or a number of liquids from a flowing medium. Its advantages are close control of porosity and relatively high strength. Assembly is often aided by bonding the material during sintering to solid metal (steel or copper) which can be machined, ground, or threaded for individual requirements.

(9) *Metal-to-Glass Seals.* Expansion coefficients can be more closely controlled through powder metallurgy than through casting;

therefore, the powder metallurgical method is often preferred for making glass to metal seals such as Fernico.

(10) *Metallic Coatings.* There are many processes for preparing metallic coatings. Iron is coated with corrosion-resistant metals, such as monel metal and 18-8 stainless steel, by casting them on iron in a mold. Copper is electroplated on stainless-steel cooking utensils to increase their thermal conductivity and to produce a perfectly uniform temperature over the entire bottom of the pot or pan. Duplex thermostat metals are made by brazing one metal to another and then hot rolling. Heating metal plates, such as platinum and iron (in hydrogen), applying pressure, and then hot rolling has been used to produce iron-backed platinum contacts for the Payne mercury switch.

A method of preparing metallic coatings with powder metals emerged from the research stage in 1952. It consists of spreading a layer of metal powder of the thickness desired on the surface of a sheet of metal, such as iron, chromium, or stainless steel, and then heating in a hydrogen atmosphere for a short time (10 to 20 min) at some temperature below the eutectic temperature of the elements, or at some other suitable temperature where eutectics are not involved. Subsequent cooling and cold rolling are combined with periodic anneals at the coating temperature. It is essential that the metal surfaces and powders be perfectly clean before attempting the process.

Copper, nickel, silver, tungsten, molybdenum, chromium, cobalt, and 18-8 stainless-steel powders have been put onto iron and rolled into sheet form. All except molybdenum have been rolled from ⅛ in. or more to 15 mils (0.015 in.) or less. Molybdenum causes the most trouble in rolling to thin sheets. Tungsten or cobalt on iron can be cold rolled to a certain point and then must be finished by heating to about 500 or 600 C. Iron coated with 18-8 stainless steel, rolled from about 180 mils, and having approximately 1 mil of stainless steel on the finished surface is corrosion resistant to 50 per cent nitric acid applied to the stainless steel. Thus, almost any coating metals can be used and a pore-free surface can be obtained. This process gives promise of having a wide general application as well as some very special ones.

(11) *Mixtures of Metal Powders and Other Materials.* It has been found that nonmetals can be pressed and sintered with metals to form materials with new properties. Diamond-impregnated cemented carbide has been developed for oil-well drills and grinding-wheel dressers.

Graphite has been added to powdered iron for better bearing properties. At high enough sintering temperatures, iron and graphite form steel. The possibilities for invention in this field are enormous.

A new field still in the development stage is the production of mixtures of metal powders and ceramics. These products, termed *metamics*, possess resistance to high-temperature oxidation and combustion gases typical of ceramics with improved thermal conductivity and shock resistance associated with metals. Although the powder metallurgy method is applicable, production by slip casting (Chapter 13) is also employed.

16.9 MECHANICAL PROPERTIES AND DESIGN

The physical and mechanical properties of a sintered part depend on the composition of the powder mixture; the grade of powders used; the temperature, time, and atmosphere of sintering and resintering operations; and the density resulting from briquetting, sintering, and sizing operations.

The tensile strength, impact strength, hardness, and ductility of a metal-powder product increase with increasing density of the product, provided that the same powder mixture, quality of powder, and sintering treatment are used. With present techniques, excepting for infiltration, increased shrinkage accompanies the higher densities. Consequently, there is a compromise required between high strength and close tolerance (see Fig. 16.2).

Sintered products are not generally sold with guaranteed mechanical properties, due to density variations which arise for different part sizes and shapes, unreliability of test bars, and difficulty of obtaining a test specimen from the average part. Typical properties of four iron compositions are given in Table 16.1. These properties are

Table 16.1   Typical Properties of Four Powdered Irons *

Type	Tensile Strength, psi	Elongation, %	Impact Strength, in.-lb †
Low carbon	19,500	3–4	27
Low carbon, copper impregnated	49,000	2–5	102
High carbon	28,000	0–1	25
High carbon, copper impregnated	74,000	0–1	88

* Properties listed are averages for 10 specimens each. Variations are as high as 10 to 25 per cent between pieces.

† ½ x ¼ x 1½ in. test bars, no notch.
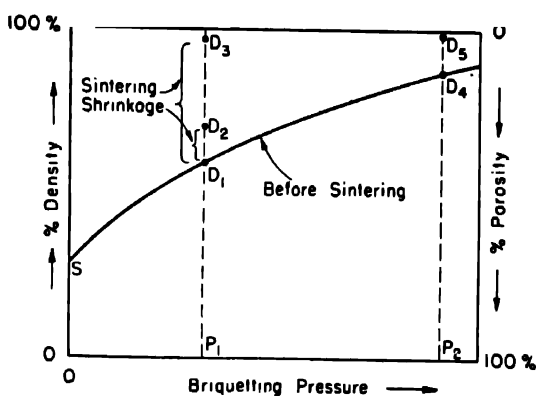
FIG. 16.2. (a) Briquetting takes place from start, S, to density, D_1, and pressure P_1. Sintering increases the density to D_2 (which is desirable for porous bearings) or longer and more careful sintering may increase the density to D_3 with an accompanying large shrinkage. (b) To obtain a high density (and thus good physical properties) without great shrinkage, briquetting may continue to density D_4 and pressure P_2. This procedure requires only a small volume change to D_5 during sintering, but involves much greater expense.
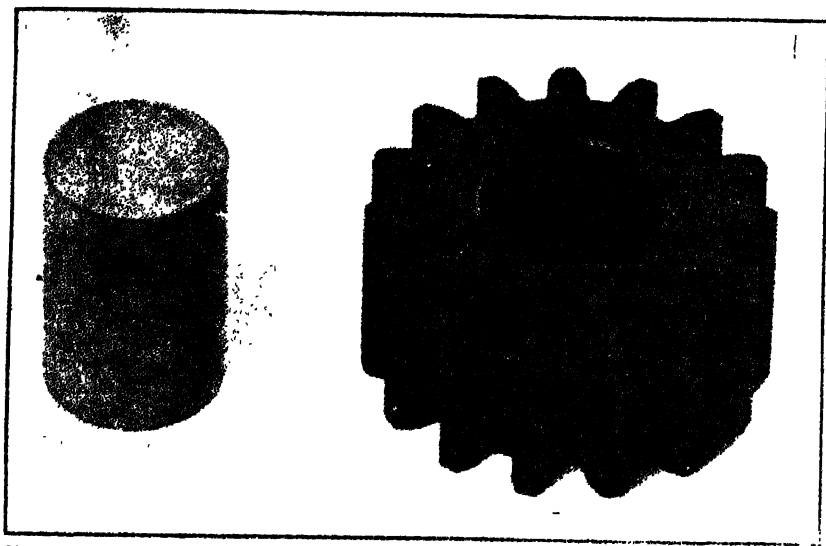
FIG. 16.3. Parts for impregnating a pinion gear for a clothes washer. The copper-alloy slug at left is placed in the gear bore. Both are then heated in a reducing atmosphere until the slug melts and infiltrates the part.

FIG. 16.4.   Photomicrograph of structure at center of impregnated pinion in
Fig. 16.3. Light areas are copper. Dark areas show
pearlite, and segregated cementite and ferrite. ×500.

averages for 10 specimens each but the variations between specimens
are as much as 10 to 25 per cent. The low-carbon iron contains up to
0.3 per cent carbon and the high-carbon iron up to 1 per cent. Note
the improvement in properties obtained by
copper impregnation. Typical low-strength
irons generally contain carbon up to 0.3 per
cent. Medium-strength irons contain up
to 1 per cent carbon. High-strength irons
have 1 per cent carbon and are impregnated
with up to 30 per cent copper (see Figs.
16.3 and 16.4). The hardness of these irons
varies widely and, in general, hardness is
not a good indication of other mechanical
properties. Elongation varies with the al-
loy: in general it is low, ranging from 1 to
2 per cent, but may exceed 10 per cent in
some of the high-strength alloys.

FIG. 16.5.   Diagram show-
ing length, l, and width, w,
of briquette formed be-
tween punch and die walls.
Decreasing l/w increases
the density.

   Uniformity. The uniformity of density
is one of the most important features for

the designer to consider. The density of pieces of different sizes and shapes will vary even with identical briquetting and sizing pressure. This is because the pressure is usually applied along only one axis. Thus, the density will be affected by the friction between powder and die in two ways: (1) If the ratio of l/w (as shown in Fig. 16.5) is
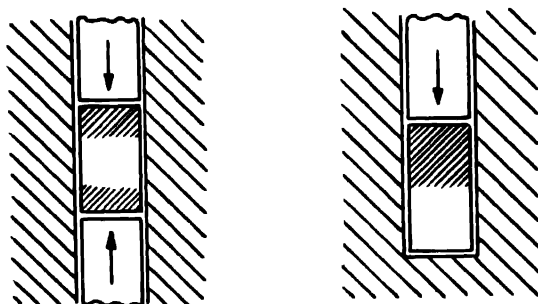
FIG. 16.6. Diagram showing the uneven density distribution caused by a relatively large l/w in pieces briquetted from one or both ends. Shaded area is the region of higher density.

low, the density will be greater. (2) If the ratio of l/w is high (in general greater than 2), the density distribution will be uneven. If pressed from both ends, the density will be low in the middle. If pressed from one end, the density will be low at the opposite end (see Fig. 16.6). When the length, l, varies across a given piece, the density will be greatest where l is small. To get uniform density distribution in this case, more than one punch may be needed (Fig. 16.7). Multiple punches increase the expense and should be required only when the mechanical properties of the piece are important.
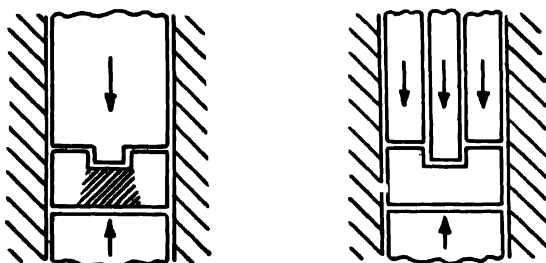
FIG. 16.7. Diagram showing the need of multiple punches in order to get a uniform density distribution with a nonuniform section. Single punch at left produces dense region (shaded area) directly under the punch. Three punches at right give more uniform density.

Thin Sections. Wall sections as thin as 0.022 in. have been produced in hubs ⅜ in. long, but 0.050 in. is usually considered the minimum up to ¾ in. diam, and higher values for larger pieces. Thickness parallel to the compression axis should be at least 0.032 in., although, again, 0.050 in. is more satisfactory for ready production. Narrow or deep splines (see Fig. 16.8*A*) are to be avoided due to the difficulty of ejecting the compact from the die. Transitions between sections that must be of unequal thickness (see Fig. 16.8*B*) should be as gradual as possible to prevent die wear and hazard of warpage and breakage in sintering and handling.

Holes. Moderately shaped or tapered holes or keyways in the direction of pressing are standard design. Holes normal to the pressure axis must be machined after sintering.

Re-entrant Angles and Undercuts. Re-entrant angles and undercuts must be machined after sintering (Fig. 16.8*C*). This applies to inside or outside threads.

Bevels and Radii. Beveled outside edges should be kept as flat as possible and outside edge radii should be avoided or made as small as possible, as feather edges on the punch are required to produce these features (Fig. 16.8*D*). This results in burring of the part and eventual rupture or rolling-over of the punch edge. In general, any design requiring a feather edge on the punch should be avoided. Inside corners should be beveled or filleted wherever possible so that the punch edges can have a bevel or radius.

Depressions, Bosses, and Counterbores. Where possible, depressions, bosses, and counterbores should not be more than one-quarter of the length or section thickness, and should have a minimum taper of about 0.008 in. diameter per in. of length (Fig. 16.8*E*).

Lateral Projections and Steps. Lateral projections near the top or bottom of a part are standard design. Successive steps should each be at least ³⁄₃₂ in. larger in diameter than the preceding step. Lateral projections near the center of the body are to be avoided because of the complicated dies and punches necessary to produce them.

Inserts. Inserts are not usually molded in place; they are pressed in after sintering.

16.10 CONCLUSION

The powder metallurgy process is especially suited to the manufacture of high production parts that would normally be machined from bar stock or castings by methods other than automatic screw

AVOID	AVOID

A — Avoid designs requiring very narrow and deep splines, as shown above. These splines are very difficult to mold.

B — Large and abrupt change in thickness. Uneven cross sections.

C — Reentrant groove. Cannot be molded in this form. Mold with straight sides. Machine as per dotted lines.

D — Die. Feather edge. Part. Avoid parts that require feather edges on die.

E — Wall taper 0.008″ per inch. Depression, counterbore, and boss.

F — Undercut. Hob tooth. Undercut. True involute gear tooth form, which is impossible to hob, due to profile undercut, can readily be molded as a profile part.

Fig. 16.8.   Some design details for powder metallurgy parts.

machine and multiple-spindle operations. It is not generally competitive with sand, permanent-mold, or die casting, where little or no machining is necessary. Precision casting applications are occasionally well suited economically to these processes, provided that the shape is not too intricate.

It should be remembered that many design features that are impossible if the part is to be machined from solid stock are possible in powdered metal parts. Therefore, it is expedient to consult the producers during the initial design of a part, so that all their suggestions can be included. Where tests are necessary to determine serviceability of the powdered metal, a test part may be machined from a blank of the desired composition, thus avoiding high die cost until the design is proved.

Review Questions

1. What are the two main industrial uses of powder metallurgy?

2. Why is low porosity desired for some metal-powder parts and considerable porosity desired for others?

3. List three advantages and three disadvantages of using powder metallurgy for structural parts.

4. List four special applications of powder metallurgy.

5. How can high density be obtained without high shrinkage? Why is this not always done when high density is required?

6. Why are multiple punches sometimes necessary?

7. Indicate whether the following are desired or not desired for powder metallurgy parts. (a) Long thin part. (b) Narrow deep spline perpendicular to flat section. (c) Groove at middle of bushing O.D. (d) Radius on top edge of bushing. (e) Undercut in through hole. (f) Undercut in tooth profile perpendicular to flat section. (g) Uneven cross section. (h) Section 0.020 thick. (i) Tolerances ±0.003 in direction of punch. (j) Step with large change in thickness.

17 HEAT TREATING

17.1 INTRODUCTION

A heat-treating process includes, broadly speaking, any operation or combination of operations involving heating above room temperature and cooling to room temperature and below for the purpose of obtaining desired properties in a metallic material.

Usually, a finished part or mill product is given a heat treatment to produce some desired change in structure. The change obtained may be in nature of the structural constituents, or in their size, form, or distribution. Such treatments are the types described in Chapters 1, 2, 7, and 8 for recrystallization annealing, for homogenizing, and for case, surface, and through hardening of either ferrous or nonferrous metals.

Heat treatments are also employed for other purposes, wherein structural changes are very minute if detectable at all. Typical of these operations are stress relief, embrittlement and stabilization treatments, shrink fitting, and retarding of age hardening.

The processing schedule depends on the goal to be attained. The operations involving structural changes typically include heating, holding at some temperature, and cooling at a desired rate. These operations may be employed in repetitive combinations, as in the hardening and tempering of 0.45 C steel, or the solution treating and artificial aging of Duralumin. Temperatures and rates of heating and cooling depend on the specific metal or alloy and the purpose of the treatment. The same is true of the operations that do not involve structural change as their objective.

In this chapter, the equipment used for heat-treating processes is described. Following are discussions of limitations on heat treatment imposed by design, heat-treatment specifications, and a brief review of heat-treating operations that do not promote significant structural changes.

Heat-Treating Equipment

17.2 BATCH-TYPE FURNACE

Furnaces of this type may be classed broadly as horizontal or vertical, depending on the direction in which the work is introduced.

The horizontal batch furnace, known as the *box* furnace, is the oldest and still the most common type. It consists of a horizontal heating chamber of rectangular section, charged and discharged through a door or opening in front, the bottom being known as the "hearth." The low-temperature oven (up to 1200 F) is provided with a circulating fan for speed and uniformity of heating. The medium- (1200 to 1850 F) and high- (over 1850 F) temperature furnaces may be provided with special gaseous atmospheres, suitable for brazing, sintering, and carburizing as well as for hardening and annealing. The larger furnaces may be furnished with car bottoms to facilitate charging.

The box furnace is characterized by simplicity of construction and operation, low first cost, good thermal efficiency, low maintenance cost, and adaptability to a wide range of work. Its chief disadvantages are poor utilization of working space and difficulty in handling long slim parts without sagging or warping.

The vertical batch furnaces are usually cylindrical in shape and are of either the pit or the bell type. The *pit* furnace is placed partly or completely below the floor level, and opens at the top. It is particularly suitable for heating long parts such as tubes, shafts, and rods suspended from a top supporting fixture, or supported from the lower end and held in a vertical position. Loading in this manner gives minimum warpage. The pit furnace is also convenient for parts such as gears and sprockets which can be loaded in containers or on suitable fixtures for charging and discharging. The *bell* furnace consists of a cylindrical heating chamber, open at the bottom, which is lowered over a retort, covering the work during both heating and cooling. Since the cooling operation is slower than the heating operation, one bell furnace can take care of several retorts. Furnaces of this type are especially suitable for annealing coils of strip or wire. For dense furnace loading, both types are provided with a motor-driven fan for circulating the furnace atmosphere, to provide more rapid and more uniform heating.

A variation of the vertical-type furnace is the *elevator* type. It is a car furnace with an opening at the bottom. The charge is loaded

Table 17.1   Some Heat-Treating Reference Points

Useful Temperature Data

These data were obtained from the following publications and companies: *ASM Handbook*, 1948 edition; Bethlehem Steel Co.; *Handbook of Chemistry & Physics*, 24th edition; Linde Air Products Co.

HEAT-TREATING TEMPERATURES	DEGREES FAHR	CENT	MELTING POINTS AND OTHER IMPORTANT TEMPERATURES	COLORS
	2800		Melting point iron	HEAT COLORS
		1500		
	2700		Beginning of solidification. cast steel (0.20-0.40%C)	
Approx sintering range cemented carbides	2600			
		1400		
	2500			
			Melting point Monel ('B')	
	2400		Beginning of solidification gray iron	
		1300		White
	2300			
Approx hardening range (W- high-speed steel)				
	2200	1200		
Approx. hardening range. (Mo- high-speed steel)			Upper limit of pouring range: cast aluminum bronzes	
	2100			Light yellow
	2000	1100		
			Melting point copper	
	1900		Melting range silicon bronzes	Bright yellow
Forging temp. common NE steels		1000		
	1800		Approx solidification point. red brass, SAE 40	Bright orange
Approx. graphitizing temp. for malleablizing white cast iron	1700		Melting range: high brass (66-34)	
		900		
Case-hardening range: low carbon steels	1600		Melting point: Tobin bronze	Bright red
Normalizing temp. common NE steels				
Hardening temp: carburized NE 8620, 8720 & 9420 steels				
	1500		Flow point· silver solder (20%Ag)	
Hardening range: non-deforming oil hardening tool st		800		Dull red
Annealing range: gray C.I. (for max machinability)			Pouring temp. (for max. fluidity). sand cast Mg-Al alloys (5-13%Al)	
Softening range (followed by water quench) Cu-Be alloy (2-2½% Be) also used prior to hardening for welded or hot worked parts	1400			

Table 17.1 Some Heat-Treating Reference Points (Continued)

HEAT-TREATING TEMPERATURES	DEGREES FAHR / CENT	MELTING POINTS AND OTHER IMPORTANT TEMPERATURES	COLORS
		←Flow point : silver solder (45% Ag)	
Final heating range : malleable iron (after quench from 1700°)	1300 / 700	←Flow point : silver solder (15% Ag - 5% P)	Dark red
Upper limit of annealing range : Cu-Si alloys	1200		
	1100 / 600	←Flow point : silver solder (50% Ag - 18% Cd etc.)	
		←Approx solidification range. Al-Mg casting alloys SAE 37 & 320	Faint red
Tempering range : high speed steels	1000		
Tempering temp. 0.30% C cast steel (for max. strength)	900 / 500		
Stress relieving (mild annealing) range gray cast iron (for min change in physical properties)			Black
	800	←Pouring temp. SAE 110 babbitt	TEMPER COLORS
Heat-treating range Dural, 17S-T	/ 400	←Melting point zinc	
Pre-heating range prior to welding gray cast iron	700	←Melting range Zn alloy die castings SAE 903, 921 & 925	Steel gray-blue
		←Flow point 2-½% Ag-Pb solder	
	600	←Melting point lead	Blue-gray
Precipitation heat treatment (hardening) range. Be-Cu (after cold working or quenching from 1450°)	/ 300	←Pouring temp. "type metal"	Blue
		←Approx mechanical working temp. (punching, shearing, etc.) wrought Mg-alloys	Blue-purple
	500		Purple
Stress relieving temp. Cartridge brass (for max. physical properties)		←Completion of melting wiping solder (40% Sn)	Dark straw
Heating steel springs for stress relieving and for prevention of hydrogen embrittlement after cold working and electroplating	400 / 200	←Approx mechanical working temp. (forming sheet) Al-alloys 53S, 51S, and 27S	Straw
Stress relieving temp: deoxidized wrought Cu and high brass			Light straw
	300		
Tempering range : carburized and hardened steels (for max. hardness)	200 / 100	←Melting point. Bi solder (40% Bi)	
		←Melting point. Rose's alloy	
		←Melting point. Wood's alloy	
	100		
	/ 0		
Temp. range for arrest of age hardening in Al-alloy rivets (17S-T, A17S-T, 24S-T)	0		
Aging temperature : steel gages			
	-100 / -100	←Vaporization point : solid CO₂ ("Dry ice")	

on the car platform, the car then rolled into position underneath the furnace and raised into the furnace by means of a motor-driven lifting mechanism. For certain plant layouts this type of furnace eliminates the need for transfer cars and switching tracks, and often saves floor space. It is suited for heavy work and for the precipitation-hardening nonferrous alloys which must be quenched rapidly to retain a supersaturated solid solution. The quenching tank for such work is placed directly below the oven, thus facilitating a quick transfer.

17.3 CONTINUOUS-TYPE FURNACE

Furnaces of the continuous type are modifications of the horizontal batch type provided with a conveying mechanism to carry the parts automatically through the furnace. The fixed speed of the conveying mechanism, and the closely controlled temperature zones of the furnace make possible any time-temperature cycle of great repetitive accuracy on separate pieces. Variations in heating time, atmosphere, and temperature, introduced by the hand operation of the batch furnaces, are avoided, thus giving greater uniformity of product. The continuous-type furnaces are well suited for in-line production. Although standard sizes are available, "tailor made" furnaces are also made for specific jobs. The first cost of either is higher than for the batch-type furnace, but the high thermal efficiency, improved performance, and the adaptability to a wide variety of parts of similar size make the continuous type of great importance industrially.

There are several different arrangements—belt, roller, and rotary types. In the belt type, the conveying mechanism is a wire mesh alloy belt or a thin sheet of silicon steel. The parts are placed directly on the belt for the trip through the furnace. The roller type employs a series of rolls synchronously driven to carry the parts. If the parts are long enough, they may be placed directly on the roll table. Shorter parts are placed on fabricated trays made of· channels or rails, and for very small parts, these rails may be covered with wire or ribbon mesh. The roller type is therefore suitable for light, medium, or heavy work. In both the belt and the roller types, the work may be charged manually or automatically, and also discharged either way. In some production lines, or for shops where only one operator can be employed, it is desirable to have the charging and discharging doors adjacent to each other. This arrangement is provided by the rotary type continuous furnace. Besides the advantages

mentioned, the rotary furnace is also popular for parts that must be handled individually to assure correct quenching.

17.4 SALT BATH

The molten salt bath, one of the oldest of the devices available for heat-treating purposes, is used for (isothermal) quenching as well as for heating. Salts that are electrical conductors may be heated by passing current through the bath between immersed electrodes. The electric current not only heats the bath but also sets up circulation of the salt, which promotes uniformity of heating. Nonconducting salts are heated externally. Depending on choice of the salt, the bath may have a chemical action on the immersed part or may serve as a protective atmosphere. The salt adhering to the surface prevents oxidation during the transfer of the part to the quenching tank, but the loss of salt makes the bath operation expensive. Heat losses are also considerable. Speed and uniformity of heating are promoted by the natural characteristics of the process, and salt baths are available for all temperature ranges used in current heat treating practice. They are used considerably for annealing and aging of nonferrous strip and wire.

17.5 INDUCTION-HEATING APPARATUS

A metal object to be heated may be located with respect to a coil carrying alternating current in such a manner that the electromagnetic field of the coil will establish strong heating effects in the desired areas. The coil may be of water-cooled copper tubing, it may have a special contour to suit the shape of the part being hardened, or it may be a single turn in the form of a hollow bronze casting, as shown in Fig. 17.1.

The metal part placed in an induction furnace is heated by eddy currents within itself, and if the part is ferromagnetic, it will also be heated by its own hysteresis losses.

Frequencies range from normal 60 cycles to several megacycles. Up to 10,000 cycles, motor-generator apparatus is most common. Above this, the source of power may incorporate a spark-gap circuit to 200,000 cycles per sec or a vacuum-tube circuit to this and higher frequencies. Low frequencies are used for heavy parts that are to be heated through; high frequencies are for small parts or for those that are to be heated on the surface only since, with the higher frequencies, eddy currents are generated closer to the surface.

(a) Heating
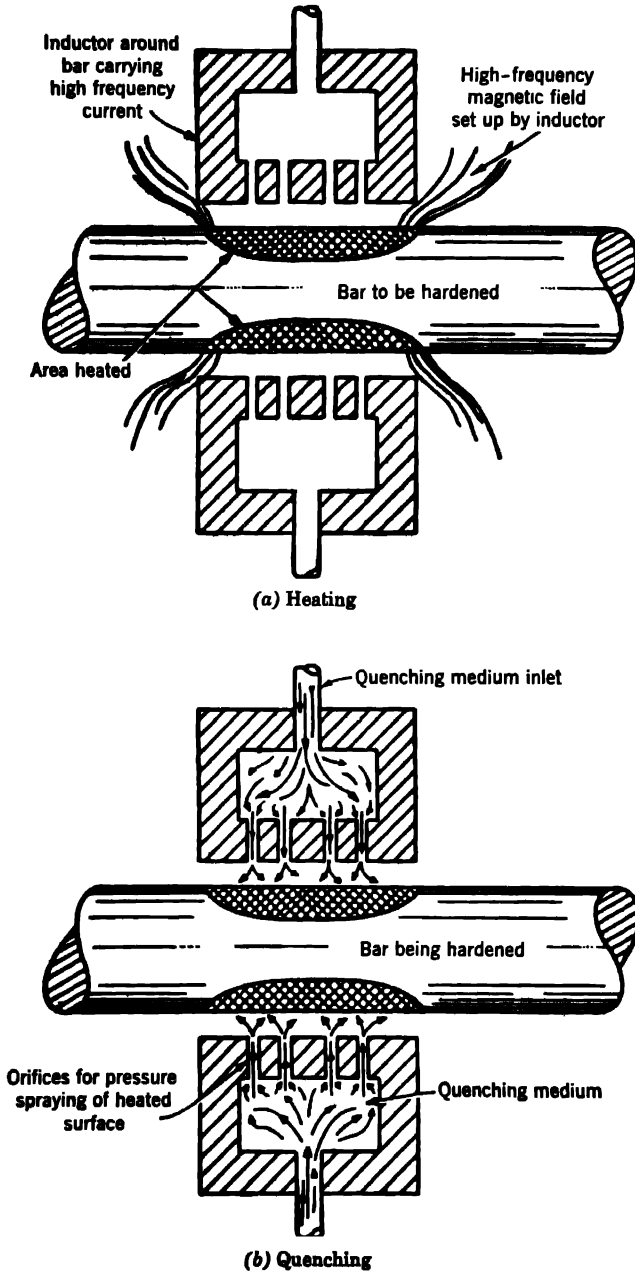
(b) Quenching

FIG. 17.1. Induction hardening part of the surface of a bar. (a) Heating cycle. (b) Quenching through induction-coil head.

This process supplied something long desired by the heat treater—a practical means of applying heat where desired and of keeping it away from areas where it is *not* wanted. Its value lies not only in the speed and efficiency, but also in the close degree of control which is possible. The nature of the induction process is such that it lends itself most readily to large-scale, repetitive production. Even so, small lots and a wide variety of parts can be handled with good results.

The heat generated in a part is entirely due to the magnetic flux created by the inductor coil (see Fig. 17.2); only by changing the intensity of the flux pattern at the part can the loading on the electronic heater be affected. This magnetic flux is directly proportional to the amp turns in the coil, i.e., the coil current times the effective number of turns. Also, since the flux density is greatest at the conductors themselves, diminishing rapidly in the surrounding space, the closer the coil is to the part the greater will be the loading. Coil design depends on the following factors, but it is necessary in all except the simplest cases to determine the final design by actual trial-and-error methods.

(1) The coil should roughly conform to the shape of the part, if no sharp contours need be considered. Symmetry is important, i.e., the part should be centered in the coil as far as possible.

(2) Sharp contours will heat first because of the concentration of flux and the lack of mass. Thus, the coil should be farthest from the part at these points.

(3) If dissimilar metals are being heated for brazing, etc., the magnetic flux must be concentrated on the slowest heating metal; in general, magnetic steel heats more easily than any other material, with stainless steel, brass, copper, and silver following in the order of their resistances.

(4) In brazing, the joint should be at the correct temperature before the brazing alloy melts, so that it will be drawn into the joint. Thus, a concentration of heat on the brazing alloy should be avoided.

(5) Generally it is not economically feasible to construct electronic heaters with a circulating current in the resonant circuit above approximately 300 amp. Double-bank coils are sometimes necessary in hardening because of these current limitations. Since the outside layer of turns is far less efficient than the inner layer, such coils should be used only if essential.

(6) To obtain uniform heating at the circumference of a disc or bar, rotating the parts is advisable in order to avoid the heating effects of the coil leads.
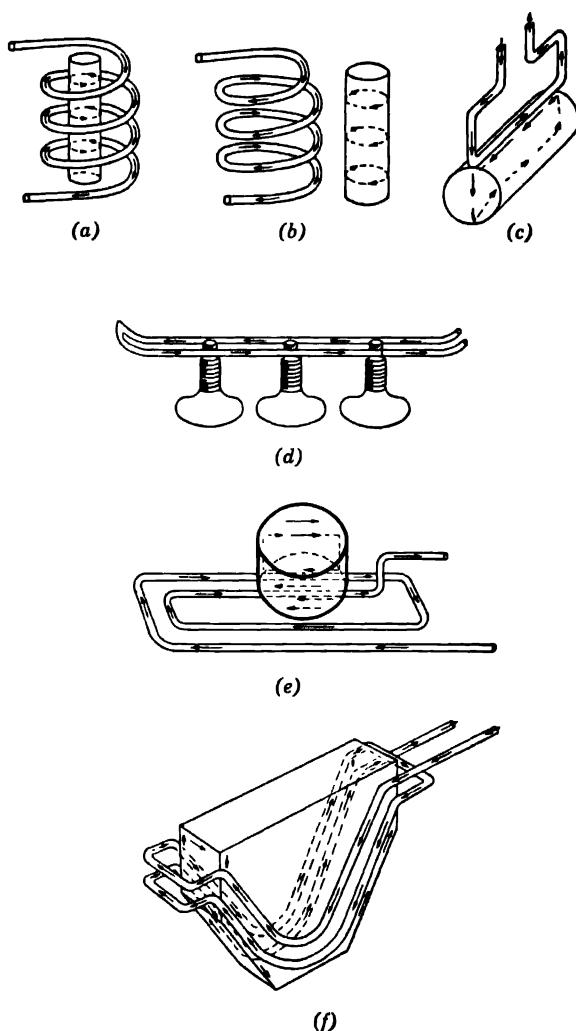
Fig. 17.2. Sketches showing direction of current flow in induction-heating coils and in parts being heated.

(7) The number and size of coils that can be used on any equipment are determined by two factors; the power capability of the electronic heater and the maximum inductance allowable.

One very promising application of induction hardening is for the teeth of large gears. Proper heating and cooling cycles on hardenable alloy material make possible a hard wear-resisting surface having residual compressive stress. This stress opposes the tendency of the wiping action to open surface cracks and reduces pitting which would be caused by forcing lubricant into the tiny surface openings during service.

17.6 FLAME HARDENING

This method has also been used for hardening gear teeth and other intricate shapes. A steel having the necessary hardenability is chosen, as before, and the surfaces to be hardened are heated by a specially adapted gas welding torch, the torch flame being adjusted so that the steel does not oxidize. The surface is heated so rapidly that it passes through the critical temperature, A_3, before the interior is affected. For many parts the quenching action of the adjacent cold metal is sufficient to produce the desired surface hardness. External quenching, when needed, must be done immediately and it is usually followed by tempering to relieve the quenching stresses.

17.7 SURFACE PROTECTION

Solid, liquid, and gaseous media are used to protect parts from surface oxidation during their heat treatment. Cast-iron chips and carburizing compounds are two of the most common solid materials, and the protective action of liquid baths has already been mentioned. Gaseous media (controlled atmospheres) for heat treating are of later development. The choice and control of gaseous media are very critical because some of the gases that prevent oxidation and scaling in steel generally cause carburization or decarburization also, which may prohibit their use.

17.8 COOLING OR QUENCHING

Water, oil, and air are the universal quenching media. The relative cooling power of these three agents is about as follows:

	Cooling Power *
	(H)
Water	2.50
Oil	0.50
Air	0.02

* Grossmann, Asimow, and Urban, *Hardenability of Alloy Steels*, Am. Soc. Metals, 1938, p. 124.

Because of the rapid rate of cooling, which may reach 6000 F per sec at times, quenching is the most critical operation encountered in heat treating. It is here that the equipment, and, more important, skill and experience in manipulation count the most. Particularly in water quenching, but with other media as well, the part must be handled to come into contact with fresh fluid at all areas during cooling, since a static area will soon lose its cooling power, and with water may even have an insulating steam layer.

Molten salt baths, very often the same ones used for heating, may be used, particularly for isothermal quenching operations. Slower rates of cooling, when required, may be had by embedding in an insulating or retarding medium such as dry sand, lime, ashes, or mica dust. Still slower rates of cooling are obtained by holding the charge within the furnace, applying just enough heat, if necessary, to obtain the cycle desired.

17.9 SUBZERO COOLING

Three types of cooling media are in use for obtaining subzero temperatures in metallurgical processing. Dry Ice (carbon dioxide) vaporizes at -110 F and is suited to many uses because of its low cost and ease of handling. Temperatures to -150 or -160 F are now obtainable with special mechanical refrigeration equipment having 1000 to 2000 Btu per hr capacity. Minus 175 F is often obtainable with this equipment but at lower capacity. The use of liquid nitrogen attains still lower temperatures to -320 F. With these three methods, the subzero temperatures required for stabilizing, shrink fitting, etc., can easily be obtained.

17.10 AUXILIARY EQUIPMENT

Every furnace should be provided with pyrometers to indicate, record, and control the furnace temperature. Gas-processing equipment is also used when the furnace is to be furnished with a protective atmosphere.

Associated with the heat-treating process is equipment for determining hardness, detecting cracks, and performing other tests; and, in many shops, equipment for cleaning, plating, welding, and forging.

Heat treating was formerly carried out in separate departments— often in some dark, hot, smoky, noisy, messy corner of a building— but today the trend is toward heat treating in line of production. Contrary to what one might suppose, this does not always mean expensive continuous equipment—the small batch-type furnace also has

its place in such operations and electric induction heating is contributing more and more toward this desirable end.

Design

17.11   RELATION OF DESIGN TO HEAT TREATMENT *

The fundamental principles of good design from a heat-treatment standpoint are quite simple. A metal has a certain strength depending upon its analysis, quality, and the heat treatment to which it has been subjected. When subjected to a combination of forces beyond its ultimate strength, it cracks or fails, owing to the combined action of (a) the internal stresses set up during fabrication and heat treatment of the parts, and (b) the external forces of service.

Sometimes the internal stresses alone exceed the strength of the metal and the parts crack in hardening. Or the internal stresses may tax a high percentage of the total strength, and failure will develop in service under relatively light loads. The useful strength of a part therefore decreases in proportion as the internal stresses increase.

These internal stresses arise from many causes, but the most serious, by far, are those developed in quenching, as a result of differential cooling. This differential cooling, or, more accurately, temperature gradient, is the rate of variation in the temperature over a given unit distance. If, during quenching, the temperature of point A in the cube, Fig. 17.3, is 700 F, point B is 300 F, and the distance between them is 1 in., the temperature gradient between these points is 400 F per in. at that instant. The gradient is largely a function of the size and shape of the piece being quenched, that is, the design. *The basic principle of successful design is, thus, to plan shapes that will keep the temperature gradient throughout a piece at a minimum during quenching.*

The manner in which temperature gradients give rise to internal stresses in steel may be explained from dilatometer curves (see Chapter 7). The curve corresponding to full hardening registers a permanent increase in volume, whereas the air-cooling curve registers a decrease. Both conditions are obtained simultaneously when the gradient is sufficiently large, and the hardened outer shell tries to increase in volume but is held by the core which is trying to decrease. The result is enormous internal stress because a strain of 0.001 in.

per in. in steel at room temperature sets up a stress of 30,000 lb per sq in.

The reason the pieces do not break is because the hard, brittle shell is under compression. If, however, the line of demarcation between the hardened and unhardened zones crosses an external surface, edge, or corner, then the danger of breakage is very great—a principle which is of immense practical importance.
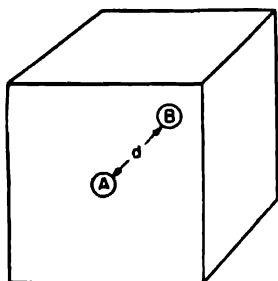
Fig. 17.3. Block illustrating temperature gradient. Gradient in degrees per in. = temp. A − temp. B divided by d in.
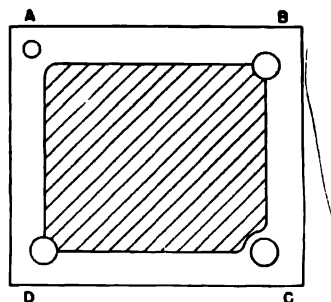
Fig. 17.4. Hardened block containing holes. Shaded part is unhardened core. Holes B and D are more likely to crack than holes A and C.

Stresses are also established in nonferrous metals by temperature gradients, but they are not as severe in most of these alloys, because there is no transformation to a new lattice type, temperatures are lower, and conductivity is higher. The following examples apply to steels that are the most critical in this respect. Nonferrous alloys, having less susceptibility, may have somewhat greater intricacy without danger of cracking.

Consider a part, having four holes near the corners (Fig. 17.4), which is to be hardened. It is often recommended that, before hardening, holes near corners should be packed with some insulating compound such as asbestos rope. If holes A, B, and D have been so packed, and C has been left open, the unhardened core will be about as shown by the shaded area. Experiments show that holes B and D are more likely to crack than A and C, presumably because A and C are contained wholly within the hardened shell, whereas holes B and D are intersected by the plane of stress which separates shell from core.

Stresses established by temperature gradients can do damage also at points remote from the junction of hardened and soft zones. Fig. 17.5a shows a section of a lamination die made of 1.10% carbon tool steel and completely hardened. After hardening, the lower right-hand corner was annealed, and (following the air-cooling dilatometer curve) it tended to shrink; whereas the rest of the metal was in the state shown by the water-quench curve. This caused a volume differential approaching 0.35 per cent, and the annealed zone, in at-
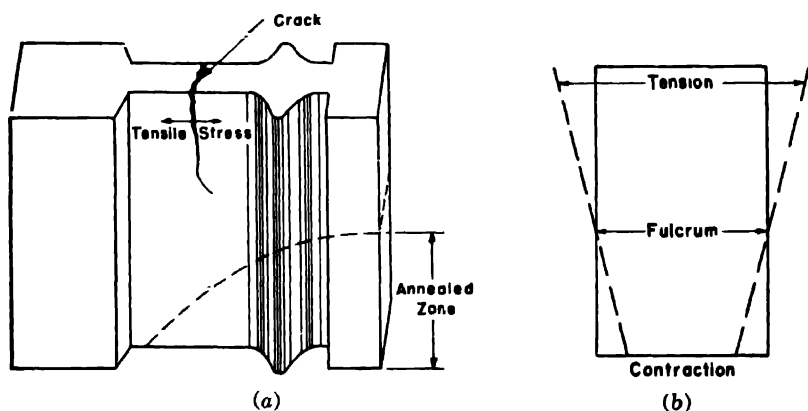
FIG. 17.5. Crack produced in lamination die, (a), as a result of tension, (b), introduced by annealing.

tempting to contract, exerted a tensile force on the top surface (see Fig. 17.5b). The top surface always cracked in the same manner: sometimes right after annealing, sometimes during grinding or assembly, sometimes during service in the presses, and sometimes only after regrinding the dies (grinding removes the surface material which is under compression, thus upsetting equilibrium). When the annealing operation was eliminated the trouble disappeared.

Some shapes are almost impossible to harden because of the abruptness in the change of sections, but a certain latitude in the design is obtained when using an oil-hardening or air-hardening steel instead of a water-hardening steel. All things being equal, the gradient between two points, e.g., A and B in Fig. 17.3, will be less in oil than in water and will be much less in air than in oil. Thus, a certain design may be perfectly safe for one type of metal and one type of coolant but unsafe for another.

Some hints and ideas for designing parts so they obey the funda-

mental principle of heating and cooling as uniformly as possible are illustrated in the following examples.

When a piece of metal is removed from the hardening furnace preparatory to quenching, it is presumably at a uniform temperature. As soon as quenching begins, the temperature is different in almost every part of the section. This difference in temperature is due to two conditions. First, the heat capacity or heat storage may be greater in one part of the section than in another, simply because there is more metal in one part than in another. This is illustrated by a tapered pin, as shown in Fig. 17.6. Obviously the point of this pin will cool faster than the heavy section because there is less heat to be dissipated per sq in. of cooling surface.

Fig. 17.6. Small end of tapered pin cools faster than large end because of ratio of surface area to volume of material.

The rate of cooling is also affected by the shape of the surface. Fig. 17.7 illustrates a piece that is quite uniform in cross section, but
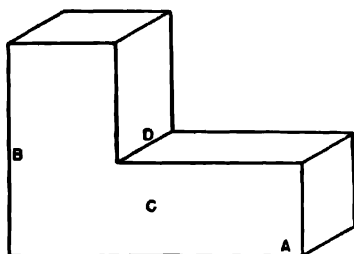
Fig. 17.7. Angle block in which edge A cools 21 times as fast as re-entrant corner D. B cools ¾ as fast as A. C cools ⅐ as fast as A.
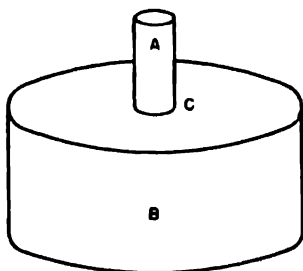
Fig. 17.8. Conditions of Fig. 17.6 and 17.7 combined, making it impossible to harden this shape in water without cracking at C.

which will not cool uniformly. The protruding corners, such as A, are cooled from three sides so that the extreme corner is giving off heat from an area approximately 7 times as great as the area from which it is receiving heat. An edge, such as B, is cooled from two sides and is giving off heat to an area 3 times as great as the area from which it is receiving heat. A point on a flat surface, such as C, receives heat from one side and delivers it to the other. The cooling area and the heating area are approximately equal. At a re-entrant

angle, such as D, heat is being supplied to the surface through three times as great an area as the one from which it is being dispelled, and this point will naturally cool last. It is impossible to get uniform cooling during the quench in the immediate neighborhood of such a sharp angle because the corner is inaccessible to the coolant, and vapor pockets may form. Differential cooling thus sets up heavy internal stresses at a point which is almost certain to receive stress concentrations in service, a very undesirable combination.

In a section such as shown in Fig. 17.8, there is a combination of the conditions given in Figs. 17.6 and 17.7. The heat capacity of the
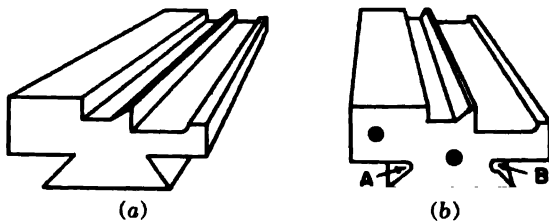
FIG. 17.9. Form tool with dovetail. (a) Unequal masses and sharp corners promote susceptibility to hardening cracks. (b) Holes balance sections, and radii at A or B reduce quenching strains.

body, B, is much greater than that of the projection, A, and there is a sharp re-entrant angle at point C. It would be practically impossible to harden such a shape in water without cracking the sharp corner. Even oil quenching would be doubtful on a piece of these proportions, and only by cooling in air could the thermal gradient be kept to a safe value.

The cross section of the tool in Fig. 17.9a consists of heavy and light sections, joined together with sharp re-entrant angles. A tool of this shape would be extremely hazardous to harden in either a water-hardening tool steel or a high-speed steel. A corrected design is illustrated in Fig. 17.9b. Holes have been drilled through the two heaviest sections, and thus the weight of the metal has been fairly well balanced throughout the cross section of the tool. The sharp angles on the cutting edge cannot be eliminated because they are a part of the form of the tool. Two suggested treatments are shown for the angle at the base of the dovetail. The best treatment is shown at A, where a generous fillet is provided. An alternative is shown at B, where the corner has been undercut to provide a radius and still give the effect of a sharp corner on the dovetail. From the stand-

point of quenching strain, the undercut form has little to recommend it, but it does have the advantage that there is no absolutely sharp corner in which stresses can concentrate.

Fig. 17.10 illustrates improper design in a double-ended side mill, or spot facer. Each side of this tool has three teeth, with the teeth placed opposite each other. This is a badly balanced condition in the cross section of the piece and is made more serious by the sharp corner at the base of the teeth. Such a tool is almost certain to break
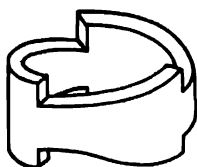
FIG. 17.10. Double-edged mill. Opposite notches and sharp re-entrant corners promote cracking.
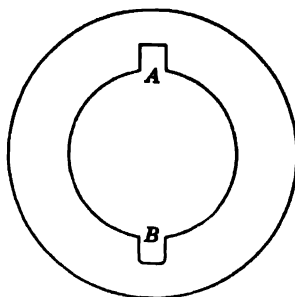
FIG. 17.11. Ring with keyways. Keyway should have round interior corners to reduce quench strain.

at the junction between the light and heavy sections. This condition may be corrected by staggering the teeth on opposite sides of the tool and introducing a generous fillet at the base of each tooth.

Fig. 17.11 illustrates two principles of design. This is a ring-shaped section containing two keyways on opposite diameters. The keyway *A* is shown with absolutely sharp corners. This is never good design. Although millions of keyways are being made and used with sharp corners, it does not alter the fact that it is a poor design for a hardened shaft and every effort should be bent toward making standard a round-cornered keyway, such as is shown at *B*.

The second interesting point about this ring is that, when it is quenched, it will not stay round. The section of the ring is weakened by the two keyways and almost invariably the ring will become oval. This condition may be corrected by cutting two more keyways at 90 degrees to the first two, as illustrated in Fig. 17.12. These keyways may serve no purpose but to balance the section and keep it round.

Fig. 17.13 shows, at *a*, the ideally sharp points on a steel-cutting tool. These points will be burned off in hardening. They should have a small flat surface as at *b*.
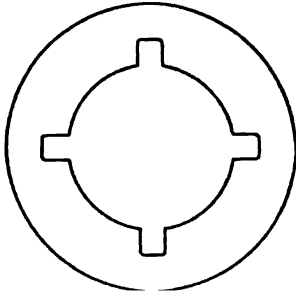
FIG. 17.12. Extra keyways added to Fig. 17.11 to eliminate out-of-round caused by weakness in vertical axis.

FIG. 17.13. Cutting tool. Points at *a* will be burned off in hardening. Flat points at *b* are better.

Success in preventing warpage and other forms of internal strain will be directly proportional to success in balancing the weight of the sections and producing uniform cooling conditions. Large dies or parts of intricate design are sometimes made in sections, which often simplifies the problem of heat treatment.

17.12 HEAT-TREATING SPECIFICATIONS

There are two errors that designers often make in heat-treating specifications. One is incompatibility in the property values specified. The other is overspecification.

When hardness and mechanical-strength properties are both specified, it is important that the values be sufficiently wide to allow for the variability of each. A better procedure is to specify one or the other, hardness specifications being the more common because of the ease of checking hardness in production.

Over-specification often occurs when the designer includes on the drawing the mechanical properties or hardness to be attained and the heat-treatment cycle to be employed. This allows the processor little, if any, latitude to take care of the variations inherent in the material composition limits and thus makes it difficult if not impossible to obtain the properties desired with the schedule specified. It is generally agreed that engineering specifications should call for the finished properties, as illustrated in Fig. 17.14, rather than to include

heating temperatures, quenching rates, etc. Exceptions to this procedure are the specifications for parts made in large volumes, where the heat-treating specification limits are determined from production lots and it is desired to have the heat-treating cycles on the part drawing for manufacturing and inspection reference.
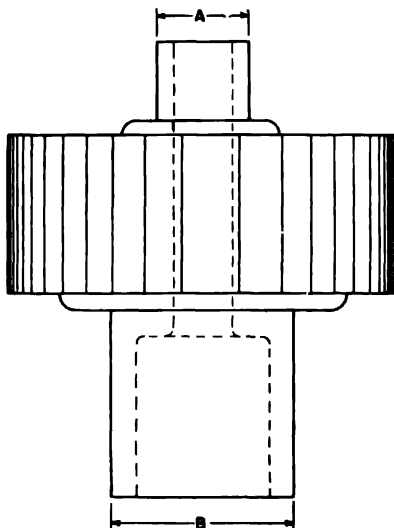
Fig. 17.14. Specification for case-hardened gear-wheel.

Allow 0.004 to 0.007 in. per side on *A* and *B*.
Finish gear and spline.
Case-harden all over 0.015 in. deep.
Hardness of case, 90–93 R15N.
Hardness of core, 45–50 RC.
Finish grind *A* and *B*.
Material (designate by system in use).

Hardening specifications for steel parts differ, depending on (1) the hardenability of the material, (2) the accuracy required, and (3) the need for toughness, hardness, or both. As explained in Chapter 7, alloy steels of high hardenability are specified for intricate parts of high hardness. Plain carbon steels are better suited to smaller parts, to less intricate hard parts, and to less toughness. When machining is to be performed on a part, annealing prior to machining is often specified if the as-cast or as-rolled state is too hard to machine. Stress relief may be specified if strains from heavy machining cuts might cause distortion in hardening. Stress relief may also be speci-

fied for cast parts or after machine straightening of hardened parts to prevent distortion during final machining. Where distortion during hardening may exceed tolerances desired in the finished part, particularly on bearing surfaces, finish machining or grinding is specified after hardening.

Normalizing is always specified for forged parts before hardening. It is also specified for large parts and high-carbon parts of all sizes to homogenize the structures prior to hardening.

Toughness in parts such as axles, shafts, gears, and bolts usually limits through hardness to 300 Brinell in medium carbon steels, and often these parts are machined completely in the hard-tough condition. Medium alloy steel gears, for example, are often machined at 33 Rockwell C and occasionally to 40 Rockwell C.

Hardness in steel parts may be specified by case-hardening, surface-hardening, or through-hardening methods. The latter is seldom used, however, for hardness alone. Usually, through hardening is specified for a combination of hardness and toughness, a wide range in these characteristics being available with different tempering temperatures. Longer time at the drawing temperature often adds considerably to toughness without penalizing hardness. Water-hardening plain carbon steels are suited to the less intricate pieces, but oil-hardening grades are required for intricate ones.

Case hardening may be specified by pack, gas, or liquid carburizing, by cyaniding, and by nitriding. Nitriding requires special material for best results but is somewhat responsive to medium-carbon grades. Pack and gas carburizing give the deepest case, and allow most grinding allowance for distortion. Liquid carburizing has less case depth but is excellent for thin sections because of the close control on depth of hardness. Control is required for thin parts so that corners and notches will not be hardened through and become too brittle for service. A general rule for thin sections is to harden no deeper than ⅛ the section thickness. Cyaniding allows only the minimum case depth and is suited for not too intricate plain carbon steel parts up to about 3 sq in. of cross section. Since allowance for grinding is about 0.003 in., intricate large designs cannot be full ground if cyanided. Nitriding produces the hardest surface with very little distortion, but cost of material and process time limit it to intricate or large pieces, which would distort too much by the other processes, or to special parts where the high hardness is desired on pieces finished before hardening. With all these methods, it is often important not to specify too hard a case as compared to core hardness. The core

must back up the case under shock, impact, and high localized compression loads, and the case will crush if too large a hardness differential exists. Parts that require straightening after case hardening and before finish grinding similarly must not have too great differential between core and case or the case will peel.

Surface hardening by induction and flame methods is usually limited to 0.45 per cent carbon and occasionally 0.50 per cent C with plain carbon or alloy steels. Hardnesses in the range of 55–60 Rockwell C are regularly obtained. Distortion is usually low by this process if the part can be rotated and heated symmetrically. Where only one surface requires hardness, the opposite surface often should be hardened too to obtain symmetrical heating and avoid distortion. Materials that will air harden in these processes aid reduction of distortion for intricate pieces. A limit on equipment that may affect choice of the process is capacity of the induction heater or width of flame nozzles, since a second pass next to a first one on stationary parts will often temper the hardness at the edge of the first pass, giving a nonuniform surface.

For precipitation-hardening nonferrous metals, similar considerations apply. Parts that are to be formed considerably are usually prepared in the annealed or the solution-treated condition. Hardening is then accomplished by natural or artificial aging. With the latter, a choice may be made in aging for maximum hardness and strength, for maximum electrical conductivity, or for minimum spring back, since the aging schedule at which these characteristics reach optimum values usually is slightly different. Because nonferrous materials are used generally in smaller parts, and because they usually can be machined in the hardened condition, in fact often better than when soft, finish machining, when required, is usually done in the hardened state. Grinding is seldom applicable. Stress relief may be specified for large castings to avoid distortion during machining, and for heavily machined parts after machining to avoid distortion during solution treatment.

The foregoing general considerations should serve as a guide to the engineer in establishing a specification for a particular material and part, based on the properties available in the material by heat treatment. The services of a metallurgical engineer, when available, should be utilized to assure best utilization of the potential properties of the material and of the available equipment.

The function of the metallurgical engineer is to advise the designing engineer as to the best material and process, and to assist the

planner, production man, and heat treater to obtain the results desired. It should be obvious that consultation between all the interested parties *before* the design is completed is bound to give better results in the long run than trying to "doctor up" and salvage faulty jobs once production has started.

Other Heat-Treating Operations

17.13 TREATMENT FOR HYDROGEN EMBRITTLEMENT OF STEELS

The term "hydrogen embrittlement," as described in Chapter 5, refers to the embrittlement of steel by hydrogen gas. It is thought that the gas present in the steel reacts with oxygen causing a bursting pressure especially at the grain boundaries. Failures of parts subject to this condition occur in a brittle fashion under light load and without or with less plastic deformation than occurs under normal static load failure of the material. The failure spreads in all directions, treelike, and follows erratic grain boundaries unlike a normal static failure, which proceeds at right angles to the maximum stress.

Embrittlement can result from hydrogen absorbed during melting and liberated as free occluded gas. It can also result from gas absorbed during heat-treating operations. The most prevalent cause is from hydrogen absorbed during acid pickling, plating, or corrosion. The intensity of hydrogen evolution in these processes increases the susceptibility, and acid pickling is nominally the worst offender. Specifications for highly stressed and plated parts, like lock washers and other springs, usually prohibit acid pickle cleaning for this reason.

In plating processes, the amount of hydrogen absorbed by the steel depends on the amount of low-hydrogen-overvoltage impurities, such as tin, selenium, tellurium, arsenic, sulfur, and phosphorus, in the plating bath. Thicker sections of steel also promote greater tendency for embrittlement because of reduced diffusion and liberation rate for the molecular gas. Increased impurities, particularly nonmetallic inclusions, in the steel also promote embrittlement.

Tests to determine whether embrittlement exists are not well formulated. Bending of parts with pliers is often used to obtain a fracture. If it occurs abruptly with subnormal deformation and has a shiny appearance, embrittlement may be indicated. Another test used is to stack flat-type springs under compression for 2 or 3 days to see if a break will occur. Still another is to subject parts to fatigue to see if embrittlement cracks exist that will lower the fatigue life.

A treatment often specified for plated parts is to bake them at 200–250 C for 1 hr or more. Greater time is used for the larger parts. This treatment gives the gas greater mobility and aids it to escape from the material. There is always the danger that the baking treatment will be conducted so long after the plating that some hair line cracks will be formed and retained in the material. As a general procedure, the best that can be done is to require low plating rates, clean baths, clean materials, and immediate baking, then to conduct sample tests of each lot of material to be sure that embrittlement has not resulted from failure to observe these conditions or from some other obscure condition.

17.14 SUBZERO STABILIZATION TREATMENTS FOR STEEL

Before extreme subzero temperatures were readily available, stabilizing of machine-tool castings was done by leaving them out-of-doors for a long time. Being exposed to the elements for one or more seasons, there usually was some zero or subzero temperatures and this followed by summer tempering was often enough to produce the required degree of dimensional stability.

With increased demand for precision in manufacturing processes, dimensional stability of metals has become an increasingly important factor. Now that the lower temperatures are more easily acquired, a high degree of stability can be obtained in a comparatively short time. In fact, what formerly took several years with the outside "seasoning" method can now be accomplished in a few hours by subzero temperature treatments and mild tempering.

The principal change that takes place in hardened steel is an increase in volume, and although a fairly high degree of stability can be obtained by resorting to several long-tempering operations, the temperatures required for this stability may be so high as to cause low hardness. This would be particularly detrimental when applied to gages, which in addition to dimensional stability also must have high hardness. It is now well known that the gradual decomposition of retained austenite in high-carbon steel is the chief cause of progressive dimensional changes, and that rapid stabilization can be obtained by subzero cooling, which, if low enough (in the order of -220 F), will transform virtually all the retained austenite to martensite. Upon return to room temperature there is a definite and regular specific volume increase because the martensite has a lower density.

This treatment can be applied to great advantage in salvaging tools, gages, or undersized parts. For example, some plug gages, $1\frac{5}{16}$ to $1\frac{15}{16}$ in. diam, made before World War I, were worn undersize part way on the front end and some had actually increased in size on the opposite end. When subjected to treatment from 5 to 15 hr at -160 F they increased in size from 0.0005 to 0.0008 in. per in. of diam, or more than enough to refinish to standard size again. It was also found that there was an increase in hardness of from 2 to 3 points on the Rockwell C scale.

Perhaps the most interesting and most controversial application of subzero treatment is its use for further hardening of tool steels. The high carbon, high cobalt types are more benefited by such treatment than the 18-4-1 (18 per cent tungsten, 4 per cent chromium, 1 per cent vanadium) or 6-6-4-1 (6 per cent tungsten, 6 per cent molybdenum, 4 per cent chromium, 1 per cent vanadium) types. It has also been found that certain types or designs of tools such as radial-relieved form cutters, worm-gear hobs, and cut-thread taps that are ground on the tooth face only will show more improvement than tools that are ground all over, particularly if they are hardened in a high carbon monoxide atmosphere. All hardened steels are improved by a proper subzero treatment to the extent that there will be less tendency to develop any grinding cracks, and, therefore, they will grind much easier after elimination of the retained austenite and the untempered martensite.

17.15 SHRINK FITTING WITH SUBZERO TEMPERATURES

Subzero methods of making shrinkfit assemblies are among the most useful applications of low-temperature treatment. Many types of assemblies may be made that were impractical or impossible with the process of using heat alone. With the use of subzero temperature to reduce the diameter of the plug, stud, or bushing, heating of the ring or outer member is either unnecessary or can be restricted to some 200–400 F. Certain steels and most of the aluminum alloys may be damaged if heated to the high temperatures required for shrinkfit assembly, but by using the cold treatment on the internal part, heating of the external part can be restricted to a point where it will do no harm.

17.16 RETARDING AGE HARDENING

An important application of low-temperature treatment is its use to delay age hardening of aluminum rivets. Heat-treated rivets of

either the 17 S or the 24 S aluminum alloys begin to age harden a very short time after quenching. To keep the rivets in a soft and satisfactory condition for driving or upsetting, it is necessary to suspend the age-hardening action by suitable cold storage. The 17 S alloy will begin to harden in about 1 hr after quenching, but for 24 S the hardening starts in about 15 min. If the rivets are stored at 32 F immediately after quenching, age hardening is suspended for about 2 days; but by using subzero of —40 to —50 F, age hardening can be delayed for several weeks. In a similar way, punched and formed parts of these alloys can be solution treated after blanking and stored at zero or subzero temperatures until ready for the forming operation. This is particularly advantageous for thin and narrow parts that may become distorted if heat treated after forming.

17.17   CONCLUSION

This chapter has covered, in a general way, the purposes of heat-treating processes and the equipment employed. Particular attention is directed to the design aspects of parts to be subjected to heat treatments and to their specifications. Together with the chapters on metallurgical properties and the chapters on ferrous and nonferrous metals, this chapter should aid the designer to work with the metallurgist, the planner, and the heat treater to obtain the maximum benefit of heat treatments in his products and to make best use of available processing equipment.

ber, and by heating the female and cooling the male member; and (*d*) retard-ing age hardening.

18 HOT-WORKING PROCESSES

18.1 MECHANICAL WORKING OF METALS

Metals are subjected to mechanical working for two general purposes:

(1) To reduce the original block or slug of metal approximately to the finished dimensions of the part or mill form, thereby saving material, machining costs, and time.

(2) To improve the mechanical properties of the metal through (a) refinement of grain structure, (b) directional control of "flow lines," and (c) break-up and distribution of unavoidable inclusions, particularly in steel.

Working above the recrystallization temperature but below the melting or burning point is termed "hot work," as described in Chapter 1. When working takes place below the recrystallization temperature, it is termed "cold work." This chapter covers the hot-working processes that take advantage of the reduced power involved in shaping above the recrystallization temperature. The finishing temperature is usually scheduled close to the upper limit of the cold-working range so that little grain growth can occur after working and the finest grain size will be produced. Cold finishing or subsequent cold-working operations are often performed, however, to take advantage of the closer tolerances and improved surface finish that result.

The hot-working processes covered in this chapter are: rolling, extrusion, hammersmithing, drop forging, machine forging, hot pressing, and hot-pressure welding. Cold-working processes such as embossing and coining, which may be used in combination with these hot-working processes, will be discussed in Chapter 19.

18.2 HOT ROLLING

Hot rolling consists in compressing and lengthening a piece of metal as it is fed between two rolls rotating in opposite directions (see Fig. 18.1). In rolling of mill forms the starting ingot is reduced to intermediate forms (see Fig. 7.14), with reheating as required. The flow

of metal during rolling is continuous and almost entirely in a longitudinal direction. Plate, sheet, and strip are commonly rolled between plain cylindrical rolls, but structural shapes (angle iron, channels, etc.) rails, rods, and bars are produced by successive passes through rollers grooved to give the desired shape. The materials commonly hot rolled are aluminum, copper, magnesium, their alloys, and many grades of steel.

Flattening, necking, and similar reductions in cross section of bars are attainable by rolling between *forging rolls.* These rolls con-

Hot Rolling   Cold Rolling
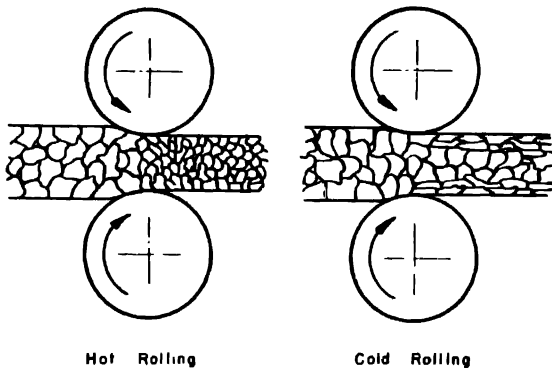
FIG. 18.1.   Hot rolling refines; cold rolling distorts grain structure.

tain the desired contour in one or more grooves, depending on the complexity. The stock is placed in the proper roll die groove, while the dies are in the open position, and the die form is imparted in less than a full revolution of the rolls. Additional passes of the stock in successive die positions produce the final shape, which may be used in this form or may be preparatory to die forging. Typical of parts processed by forging rolls are automobile rear axles, gearshift levers, connecting rods, leaf springs, and blanks for eyebolts and aluminum propellers.

18.3   PIPE AND TUBE PRODUCTION

Steel strip and plate that are rolled to the proper size for making pipe are called *skelp.* This skelp has the edges rolled in such a way that they meet in either a butt joint or a lap joint when bent into a tube before welding. Butt-joint welds cannot stand as high pressures as lap-joint welds but are satisfactory for many types of service. Butt-welded pipe is made in sizes ⅛ in. to 3 in. in diameter. The most common method of butt welding is shown in

Fig. 18.2.   The skelp is heated to welding temperature and drawn through a bell-shaped die.   The die curls the skelp into a tube and forces the edges of the seam together, causing them to weld.
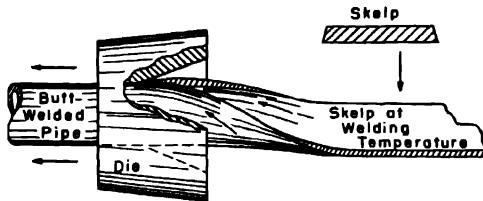
FIG. 18.2.   A common method of curling and butt-welding pipe.

Another method which is coming into common use is shown in Fig. 18.3.   The skelp is first bent into a tube, either by drawing it through a bell die or by passing through a continuous set of rolls which successively change its shape.   For large sizes the cylindrical form is obtained by rolling sideways in a set of bending rolls.   The
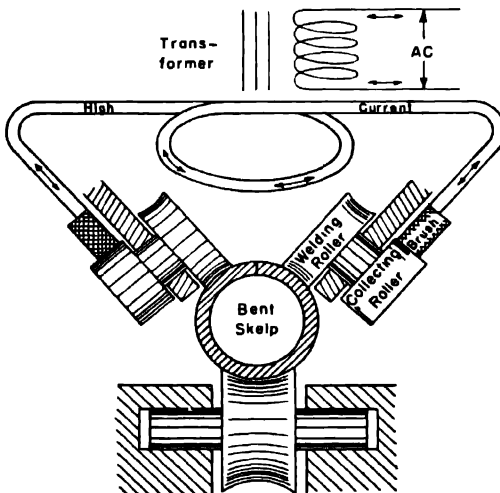
FIG. 18.3.   Butt-welding pipe seam by electrical resistance method.

bent skelp is then passed between two electrified rollers which carry enough current to heat the seam to its welding temperature.

Since a lapped seam cannot support itself in compression, the simple method of Fig. 18.2 cannot be used for lap welds.   The

original bending of the lap-weld skelp is accomplished in a bell die or in bending rolls, and then it is passed over a mandrel between rollers as shown in Fig. 18.4. The mandrel is firmly held between
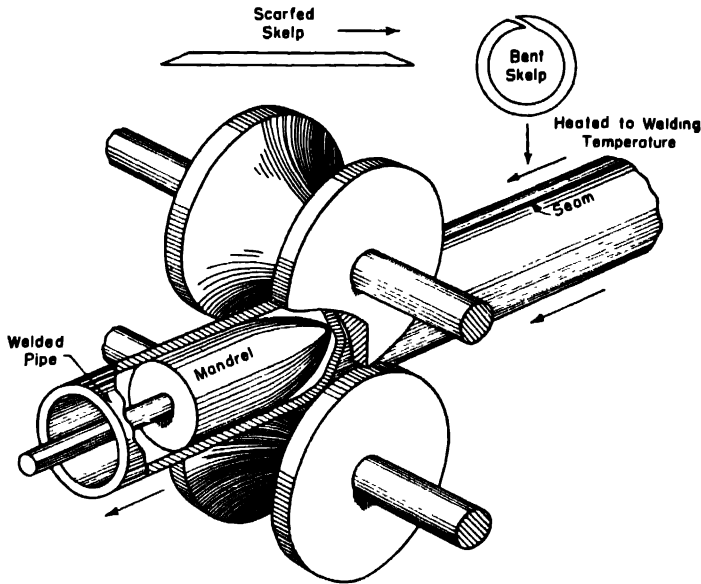
FIG. 18.4 Lap welding by rolling seam over mandrel.

the rolls, and a good weld is obtained. Pipe 25 ft long and 1¼ to 26 in. in diam is made by this lap-welding method.

Most seamless tubing is made by piercing a heated rod as shown
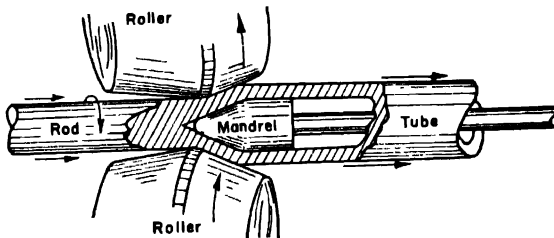
FIG. 18.5. Roll-piercing seamless tubing from solid rod.

in Fig. 18.5. The two large rollers running slightly askew rotate the rod rapidly and advance it slowly.

The alternate squeezing and bulging action of the rolls ruptures the rod at its center and the mandrel enlarges and smooths the

break. Further straightening, enlarging, and sizing are obtained by passes over a mandrel in a rolling mill and a reeler. Final sizing is usually performed cold to improve inner and outer finish. For diameters larger than 6 in., a second piercing operation is used. This is followed with a rotary rolling-mill operation, prior to finishing in reelers and sizing rolls, when the diameter is from 14 to 24 in.

Two other methods of production are used for making small-diameter tubing. One is inert-gas arc welding and subsequent sizing of inconnel sheaths for heating elements. The other is copper brazing of killed low-carbon steel tube made by crimping and rolling copper-coated strip into two layers. Both methods involve cold rolling of the stock and result in reliable pressure-tight tubing.

Hot drawing or cupping is also used for producing thick-walled tubes or cylinders. A heated flat plate of metal is first drawn in a cup in two or more drawing operations. Oxygen tanks, pots, and short cylindrical parts may be used in this shape with only subsequent necking of the open end or similar auxiliary operations. Tubing is produced by passing the drawn cup through a horizontal draw bench consisting of several dies of successively decreasing diameter. Reheating may be required between draws for long, thin tubes. The closed end is cut off after drawing and further finishing and sizing, if needed, are performed as for seamless tubing.

18.4 EXTRUSION PROCESSES

In extrusion, a sufficient pressure is applied to a metal billet or blank to cause it to flow through a restricted orifice, thus forming a greatly elongated part of uniform cross section. Either hydraulic presses or mechanical presses are used to apply the necessary pressure, the process being the same for hot and cold working.

Some typical applications of this process include hot or cold extrusion of metals of low melting point such as lead, tin, zinc, and lead-tin alloys for cable sheathing, hose casing, pipe, and solder wire; and hot extrusion of the alloys of copper, aluminum, and magnesium as rods, tubes, molding trim, and both solid and hollow structural sections of small size.

In comparison with slow extrusion under continuous pressure, there are two modifications of the process in which a rapid mechanical blow is applied. These are referred to as the "Hooker process" and

"impact extrusion." The former is usually a cold extrusion process and is commercially applied mainly for the production of small, thin-walled copper and aluminum seamless tubes and small cartridge cases. A cup-shaped slug of metal must be used, and it is extruded ahead of a punch through an annular orifice between the punch and a die. Copper tubes having wall thicknesses from 0.004 to 0.010 in. can be produced up to 12 in. length.
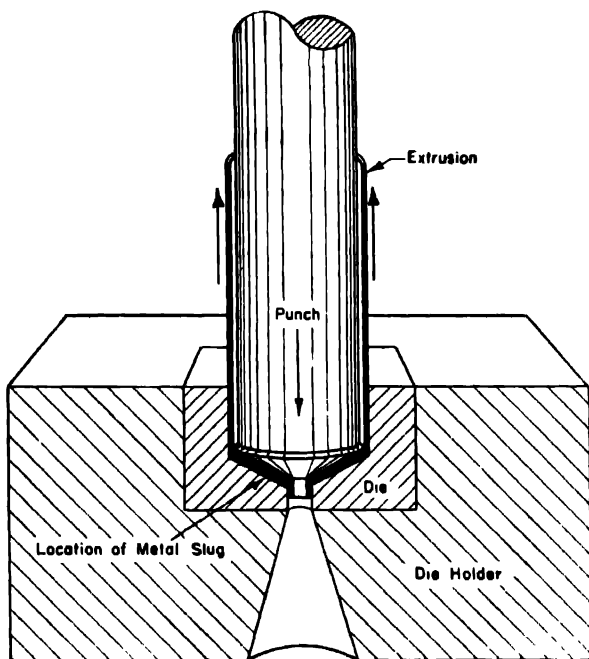
Fig. 18.6. Impact extrusion of collapsible tube.

Impact extrusion is quite similar to the Hooker process, but the flow of metal is in the opposite direction. A flat slug of metal is placed on a solid bottom die, and the impact of the punch causes the metal to flow back over the punch, which has a uniform section, slightly relieved as illustrated in Fig. 18.6. The process is applied primarily to lead, aluminum, magnesium, tin, zinc, and their alloys. Some copper and brass parts are extruded by impact, and the process for steel and nickel alloys is being developed.

About 95 per cent of the products of impact extrusion are collapsible paste tubes. Tin with 0.5 to 1 per cent Cu and some bismuth

and zinc for stiffness is preferred when it is available. Lead, usually with 3 per cent antimony or copper for strength is generally used with a tin or lacquer coating for tarnish resistance. Aluminum 99.7 per cent pure and annealed after extrusion is finding increased use for these applications.

Other applications for impact extrusions are refrigerator headers, condenser cans, dry-cell cups, transformer cups, radio shields, flashlight cases, etc. Parts may be made at rates of 35 to 70 pieces per hr and in these shapes have the pressure tightness of wrought material although they are in the soft, ductile state. Walls may be made to 0.010 in. thickness in ¾ in. diam of 2S (add approximately 0.007 in. wall thickness per in. increase in diam to 5 in.) and ³⁄₃₂ in. wall at ¾ in. diam for 51S, 53S, and 61S (add approximately ³⁄₆₄ in. wall per in. in diam to 5 in.). Designs should allow $^{+000}_{-0.006}$ in. on inside diameters, and ±0.003 to ±0.005 in. on outside diameters, with 0.001 to 0.002 taper for aluminum alloys or zinc, depending on size. Tolerances on wall width are ±0.0002 for 0.004 walls in tin and pure aluminum to ±0.003 for 0.014 in. wall. The walls may be ribbed or fluted, inside and out, but the ribbing must run the full length.

Round inside and outside corners are required at the junction with the bottom to assist metal flow. The bottom must be thicker than the walls, 0.030 in. being the thinnest for small sizes, and must have the largest tolerance ±0.003 to ±0.007 depending on size. The bottom may contain bosses, flanges or nozzlelike necks inside and out. It is preferable if these bosses can be centralized.

The extrusion usually must be trimmed because the top edge is uneven and some bulging results in stripping the extrusion from the punch. Finished lengths, 12 to 14 in., are common, but shorter lengths are required for the harder materials and smaller diameters to prevent buckling of the punch.

18.5 FORGING OPERATIONS AND PRINCIPLES

Forging is the term used to define the plastic deformation of metals at elevated temperatures into a predetermined size or shape using compressive forces exerted through some type of die by a hammer, a press, or an upsetting machine. The subject is customarily subdivided according to the equipment used for exerting the compressive force. This procedure will be followed here, but the fundamentals of metal flow common to all forging methods will first be discussed.

The raw material for any kind of forging is usually available as a bar or a billet. The desired weight for the forging is cut from this form by sawing, by hot or cold shearing, or by use of an abrasive wheel. In some upsetter and drop-forging operations a long bar is heated on one end and this end forged while intact with the bar. The forging is then separated, while hot, from the bar and, thus, cutting becomes part of the forging operation.

A number of operations are used to change the shape of the raw material to the finished form. They may be performed individually, as in smithing-type operations, or they may be combined in
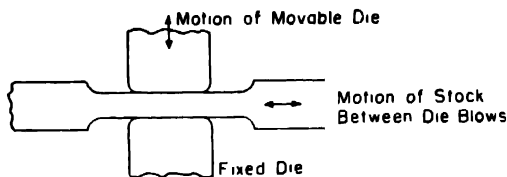
Fig 18.7. Drawing.

the action of die impressions. When successive die operations are needed, they are machined into the same die block so as to be performed successively without changing dies. The typical forging operations are:

Drawing. Drawing is a spreading, stretching, or thinning action. It is accomplished in forging by striking the work with flat dies as shown in Fig. 18.7. The impact of the dies on the metal being formed tends to reduce its thickness and increase its length and width.

Fullering. This operation is similar to drawing and is a preliminary forging operation which results in an elongated section between two heavier sections.

Edging. Edging is a gathering operation performed as shown in Fig. 18.8. Here the metal is displaced to the desired shape by striking it between two dies (Fig. 18.8a and b). As the dies strike the stock (Fig. 18.8c), metal is gathered toward the center of the cavity and some sidewise movement also takes place. The action is shown completed in Fig. 18.8d. By turning the stock 90 degrees and restriking, a section enlarged over the stock diameter in two directions is produced (Fig. 18.8e). Edging is frequently used as a preliminary drop-forging operation.

Bending. In bending there is a thinning of the material, as shown in Fig. 18.9a, accompanied by a spreading of the metal on the inside of the bend and a narrowing at the outside (Fig. 18.9b). When

(a)

(b)   (c)

(d)   (e)
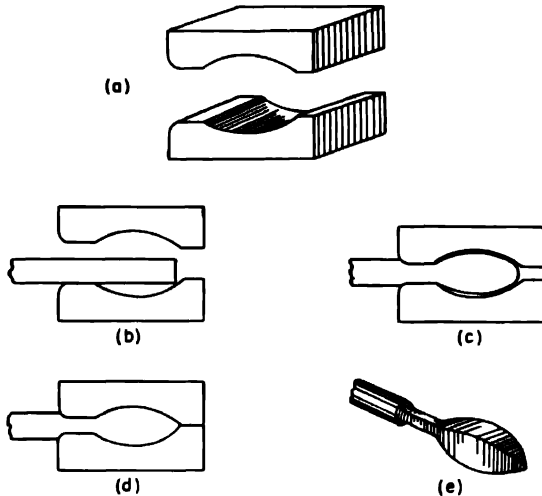
Fig. 18.8. Edging.

quantity justifies it, bending dies may be used, but for small lots the blacksmith would perform this operation over an anvil, and for large pieces and sharp bends a bulldozing machine is used. Bending is often necessary either as a final operation or as a preliminary step in fitting an upset and drawn metal section to the cavity of a drop-forging die for the final shaping.

Section A-A

(a)   (b)

Fig. 18.9. Bending.

(a)   (b)
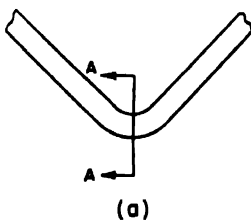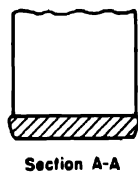
Fig. 18.10. Bars upset between flat dies.

Upsetting. A simple form of hot plastic deformation takes place when a round bar is struck axially between two flat dies. It is shortened and the metal, following the path of least resistance,

spreads out (Fig. 18.10a). Owing to the friction and chilling effect of the die faces, both of which tend to prevent deformation, the flow is restricted at the die surfaces, thus producing a bulge or barrel shape. If a square bar is upset, the square cross section is distorted, as shown in Fig. 18.10b, since the resistance to flow is less at the middle of the sides than at the corners. The bulge at the center between die faces is present as before.

Another application of upsetting is gathering of metal into a thicker section or bulge along the length of a bar. Cupped impressions in each die are employed and, by rotating the stock between blows, various sizes and shapes may be obtained.

Punching. The usual method of hot punching is illustrated in Fig. 18.11a. A blunt tapered punch is driven about halfway through the stock, displacing rather than severing the metal. Turning the piece over, the punch is driven through from the other side to meet the first hole. Only a small slug of metal is actually cut out. Where thin stock is used, the hole may be sheared by driving the punch all the way through (see Fig. 18.11b). For large holes in rings and similar parts, several punches are used, gradually increasing in size.
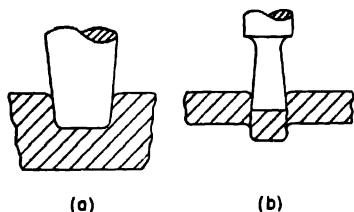
FIG. 18.11. Two methods of hot punching.

Confined Flow. All the operations discussed so far have left the metal free to flow in one or two directions while being acted upon in a third. There is an important class of operations in which the metal is ultimately confined in all directions, being forced to behave as pasty fluid in filling every portion of the confining cavity. This is the basis of drop forging and hot pressing.

Consider the deformation of a slug of hot metal placed in a die as shown in Fig. 18.12a. As the die closes, upsetting takes place as in Fig. 18.12b, only a small amount of metal moving into the hub cavity in the upper die. Shortly before the die faces meet, the metal reaches the outer walls of the main cavity and these exert a pressure which is transmitted, as in any fluid, throughout the metal, causing it to push up into the hub cavity (Fig. 18.12c). The quantity of metal in the slug is calculated to be just a little more than is required to fill the die cavity proper in order to insure a well-filled shape. The excess squeezes out into an overflow region known

as the *gutter,* which runs entirely around the periphery of the die cavity. In Fig. 18.12*d,* the excess metal is shown not quite filling the flash gutter, a proper condition.
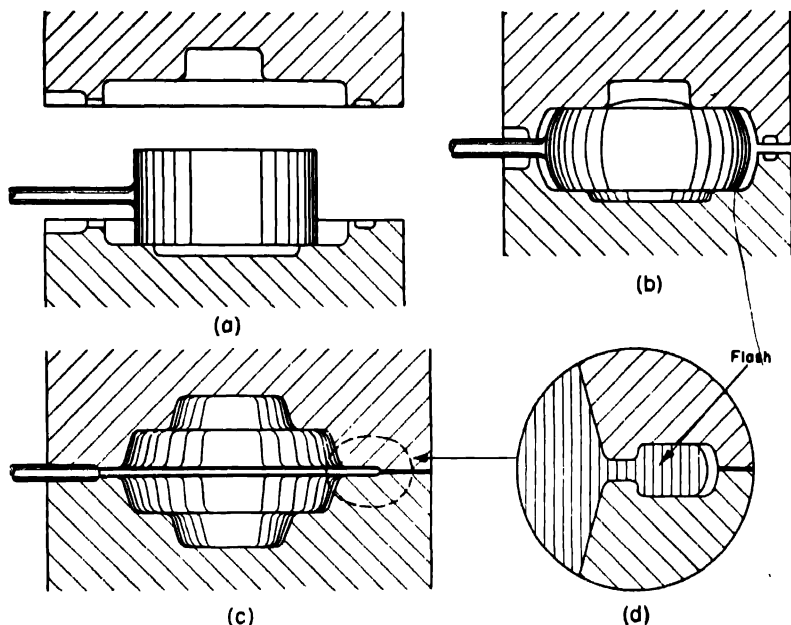
Fɪɢ. 18 12   Flow of metal in a forging die.

Blocking. It would seem that almost any shape could be produced with confined flow since the metal flows as a fluid into remote cavities. But the friction against the die surfaces, and the viscous forces in the metal become much larger as the metal is chilled and as it moves into deep cavities. If too drastic deformation is attempted, flow into the flash gutter is the path of least resistance and an incomplete forging with excessive flash is produced. This difficulty can be avoided by a sufficient number of preforming operations which distribute the metal gradually toward its finished shape. Such preforming operations are termed *blocking* operations. Their use also increase the life of the finishing die by reducing hammering and wear on it.

Finishing. This operation employs finishing dies designed to yield a forging as close to finished dimensions as heat treatment, machining allowance, and scale removal will allow. These dies are the

only forging dies whose surfaces are brought into contact with each other, producing a confined flow condition.

Trimming. The final operation in producing drop forgings is usually that of trimming the fin or flash which occurs in finishing. A lower die much like a "cookie cutter" is used in a press, and a punch roughly of the forging contour forces the forging through the lower die, shearing the flash as it passes.

Other Operations. Operations sometimes employed for convenience in obtaining the desired shape and tolerances are (a) punch-
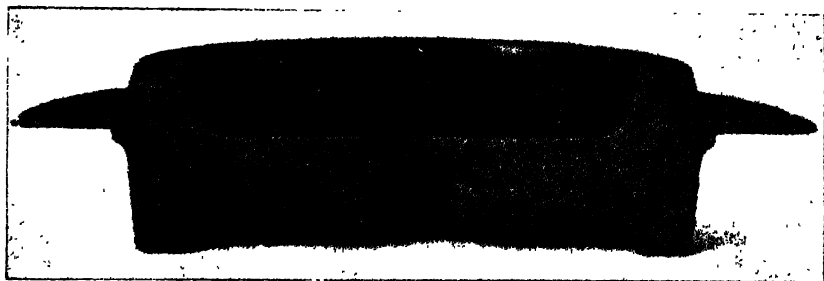
Fig 18.13. Macrophotograph showing "fiber" lines in an etched forging. (*Photograph courtesy A. H. Milne and Am. Soc. Metals.*)

ing of webs and bosses, (b) twisting or straightening, (c) reduction of draft, (d) forming, (e) coining and sizing, and (f) cleaning by shot blasting or pickling.

Grain Flow. If a hot-worked part is cut in a plane aligned with the direction of working and the surface is polished and etched with a suitable reagent, the exposed metal will usually appear to the naked eye to have a fiberlike structure (see Fig. 18.13). These fibers are really nonmetallic inclusions or segregated phases that have been elongated or "flowed" in the direction of working. Grain flow, fiber structure, flow lines, and forging fiber are terms used to describe this effect.

Tests show that certain mechanical properties are a function of the direction of the flow lines. This is illustrated in Fig. 18.14 for low and medium plain carbon steel forgings. Although tensile and yield strength are practically identical for bars cut at various angles from a forging, impact strength and ductility (as measured by elongation and reduction in area) are considerably greater for specimens parallel than for those perpendicular to the grain flow.

The proper choice of raw material and proper working of it in

forging operations make possible a fiber distribution most favorable for a part to withstand its service stresses. For example, consider a gear blank machined out of bar stock (Fig. 18.15a). The fiber is uniformly axial, but the primary service stress on the gear teeth
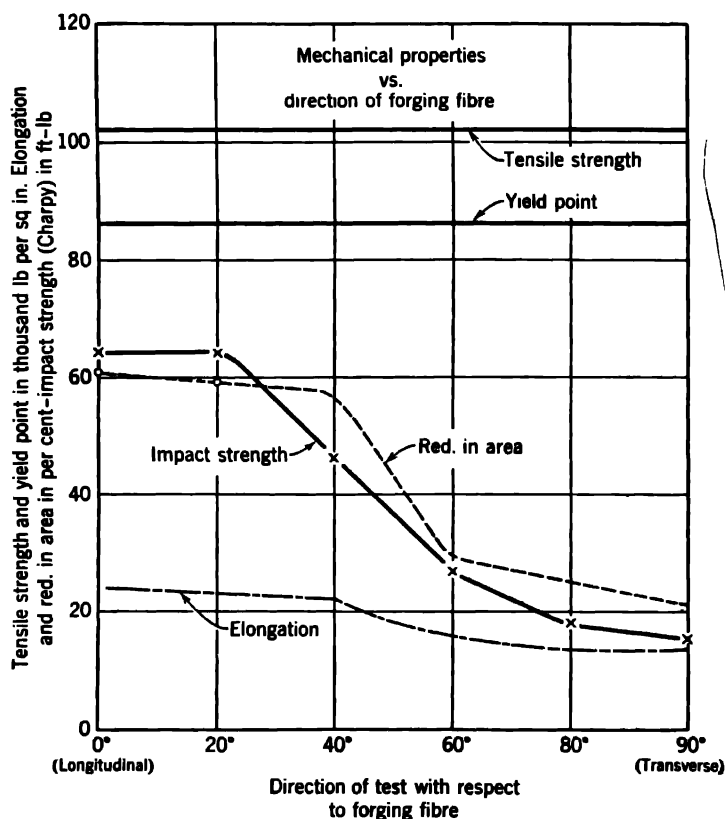
Fɪɢ. 18.14.

is tangential. By upsetting a slug as shown in Fig. 18.15b, the fibers are bulged radially, producing a fiber pattern such that the stress is placed along the fiberlike inclusions during the bending of the teeth. The transverse section of a gear blank in Fig. 18.16 illustrates how the radial fiber can be positioned to flow into the rim to strengthen the cut teeth. Fig. 18.17 illustrates how teeth of large gears may be forged prior to finish cutting, giving further strengthening by grain flow along the tooth profile. Although these examples refer to gears, they apply, of course, to other parts having
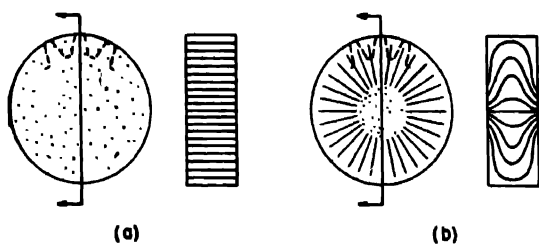
FIG. 18.15. Direction of grain flow in a gear blank; (a) bar stock and (b) forged stock.
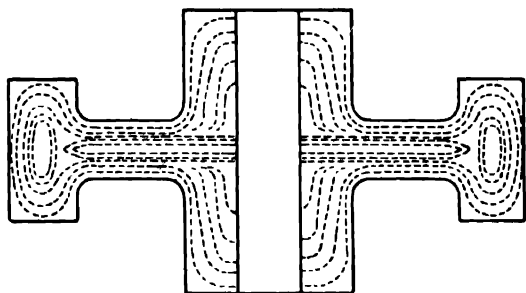
FIG. 18.16.
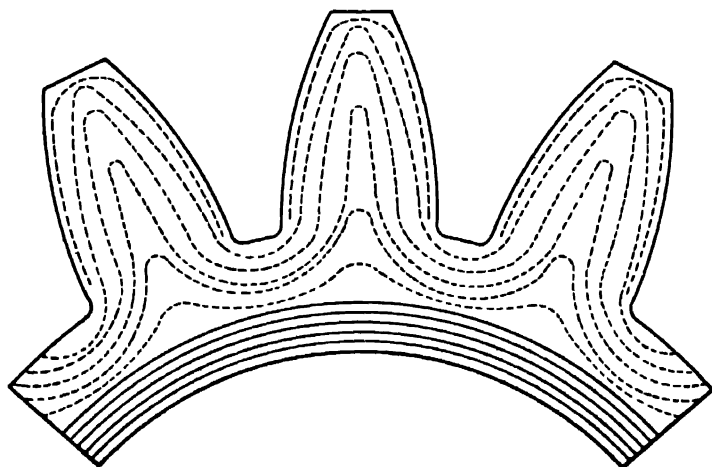
FIG. 18.17.

similar relationship between grain flow and loading. Some forgings
lend themselves naturally to correct positioning of grain flow while
on others special technique may be necessary. The designer should,
therefore, designate the grain-flow direction desired.
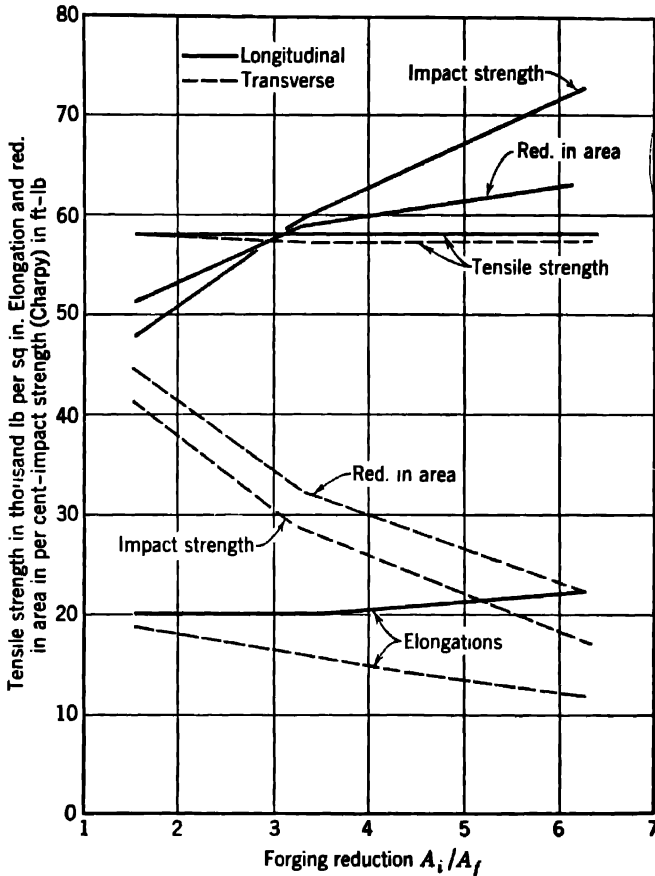
Fig. 18.18.

Mechanical properties parallel and perpendicular to the grain flow
are also a function of the reduction effected during forging. Fig.
18.18 illustrates this for low and medium plain carbon steels. Thus
the proper size of billet should be chosen, otherwise excessive direc-
tionality may result from overworking or insufficient grain flow from
too little working.

18.6 METALS FOR FORGING

Practically all metals of industrial importance can be forged successfully, but there is some difference between metals in the ease with which this can be done. Each composition has its own plastic forging range or forging temperatures. Some can be forged over a wide temperature range while other compositions have narrow ones. Compositions without a plastic range, such as cast iron, are unforgeable.

Steels. Low-carbon steels are the easiest of their class to forge. They also have better transverse properties than the harder alloys. Fine-grained ingots produce better transverse properties than coarsegrained; thus, high-quality forgings are made generally from killed, ladle-deoxidized steel showing a minimum of segregation. Typical low-carbon steels for small forgings are C1020 and C1030. C1035 and C1040 are used for medium size forgings. Forging temperatures for these steels range from 1500 to 2500 F (see also Fig. 7.15). Alloy grades and higher carbon grades are more difficult to forge, and they increase wear on dies. Forging temperatures range from 1700 to 2200 F. Typical forging compositions are 2315, 2330, 2345, 3130, 3250, E4130, E4340, 5140, 6150; for tool steels C1080; highspeed steel (18 W, 4 C, 1 Va), and alloy tool steel (0.5 C, 0.1 Si, 0.6 Mo, 0.35 Mn); for stainless alloys, types 410, 420, 430, 440, 302, and 316.

Aluminum. Forging temperatures for aluminum and its alloys range from 650 F to 900 F. Alloys 17S, 25S, and 51S are most used, and they show more pronounced directional properties than the ferrous alloys.

Magnesium. Forging temperatures for magnesium alloys range from 650 F to 800 F. Alloys Dowmetal M (AM35) and Dowmetal J (AM58S) are most used. They show even more pronounced directionality than the aluminum alloys.

Copper. Forging temperatures for electrolytic copper range from 800 to 1900 F but the alloys have much smaller ranges (250 F) lying between 1100 and 1700 F. Typical alloys forged are yellow brass with 38 per cent zinc and 2 per cent lead, muntz metal, naval brass, tobin bronze, manganese bronze (1½ tin), aluminum bronze (8 per cent Al), beryllium copper, and nickel silver (15 per cent Ni).

The high-alloy bronzes, nickel, Monel, and Inconnel, compare with the mild alloy steels in forging difficulty and die wear.

18.7   HAND FORGING

Hand forging is also known by the terms smith forging, flat-die forging, hammer forging, and blacksmith forging. It is applicable where relatively small quantities of parts are required and where the mass involved can be heated, forged, and handled by the blacksmith and his helpers. Generally speaking, the accuracy and intricacy obtainable are less than that of drop forging.

Hand forging has largely been replaced by the various kinds of power forging but it is still extensively used for repair work, particularly in the railroad industry. Among the jobs which can be done by hand forging are making and repairing crane chains, hooks, etc., bending turbine diaphragm outer rings, and making lathe and planer type cutting tools.

18.8   POWER-HAMMER FORGING (HAMMERSMITHING)

The work of the hammersmith has much in common with the blacksmith. In both, the smith's skill plays a very important part in the accuracy and uniformity of the work. The tools of the hammersmith are similar to those of the blacksmith except that the power hammer has been substituted for the anvil and sledge, and the other tools are increased proportionately in size.

The following typical hammersmithing jobs serve to illustrate the type of forging work which is performed with general-purpose dies and tools.

Large Motor Shaft. A 24-in. square ingot is first rolled at the steel mills into a square billet, perhaps 12 in. on a side. In this form a suitable length is reheated at the forging shop and then hammered across the corners, as shown in Fig. 18.19, until the final rounding
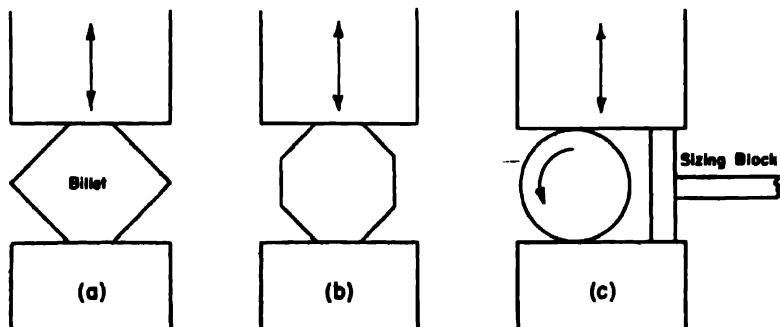
Fig. 18.19.   Forging a shaft from a square billet.

to a diameter of perhaps 10 in. is completed between hammer faces spaced by the sizing block. Reductions from 450 sq in. to less than 30 sq in. are entirely practicable by this method.

Frequently, it is more economical to stock a few sizes of material and to forge the material to the required shaft section as the occasion demands than to stock a wide variety of sizes, thus increasing carrying charges, stock space, and the payment of extras on odd shapes and small sizes.

Flange Coupling. The forging of a flange coupling blank is an application of upsetting and also illustrates the use of a hammersmith's

(a) (b) (c)
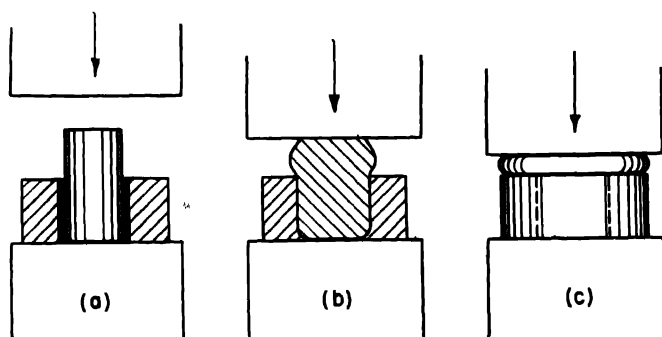
FIG. 18.20. Forging a flange coupling.

semi-general-purpose tools. Fig. 18.20 shows how the stock diameter is first upset to the coupling hub diameter inside the ring, and how, with continued blows, the flange is mushroomed outward, producing excellent grain flow for carrying tangential loads.

Rings. The operations performed in the forging of medium and large sized rings illustrate power hammer punching as well as upsetting and drawing.

Following heating and rounding up, the proper amount of material is upset until the height of the billet is about 15 per cent greater than the finished ring. A punch is driven approximately halfway through the blank from both sides as shown in Fig. 18.21. In this way the metal is displaced from the center of the blank into the wall of a ring. Successively larger punches may be used to enlarge the ring up to 12 in. inside diameter.

Rings with inside diameters greater than 12 in. are generally forged over a mandrel as shown in Fig. 18.22. As the ring approaches its
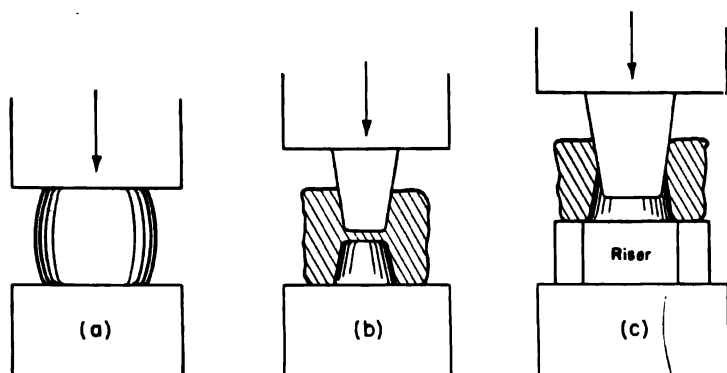
Fig. 18.21. Punching a medium-sized ring.
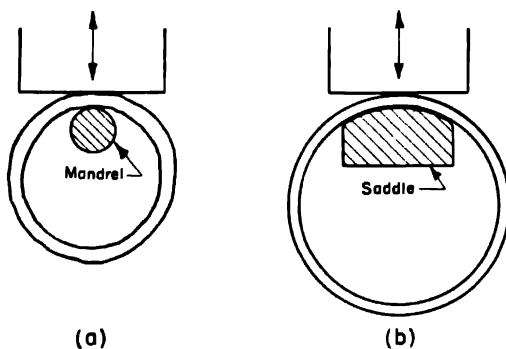
Fig. 18.22. Drawing a large ring.

finished size, a saddle mandrel is used having a radius of curvature almost as large as the inner radius of the ring.

Table 18.1

Outside Diameter, in.	Tolerance on Diameter, in.
Up to 12	$\pm \frac{3}{8}$
12 to 24	$\pm \frac{1}{2}$
24 to 40	$\pm \frac{3}{4}$
Over 40	± 1

Table 18.1 gives the tolerances to which ring forgings can be economically held. Where more than one ring forging is required of the same inside and outside diameters, it is frequently less expensive to

forge one ring of sufficient width to make two or more machined pieces, than to make individual forgings.

18.9 DROP FORGING

Drop forging is the operation in which a metal part is formed by repeated hammer blows on a bar or billet placed between a pair of dies containing the impression of the finished shape desired. Several operations, such as drawing, upsetting, and bending, may be performed in a single die. Fig. 18.23 shows a typical forging die with the
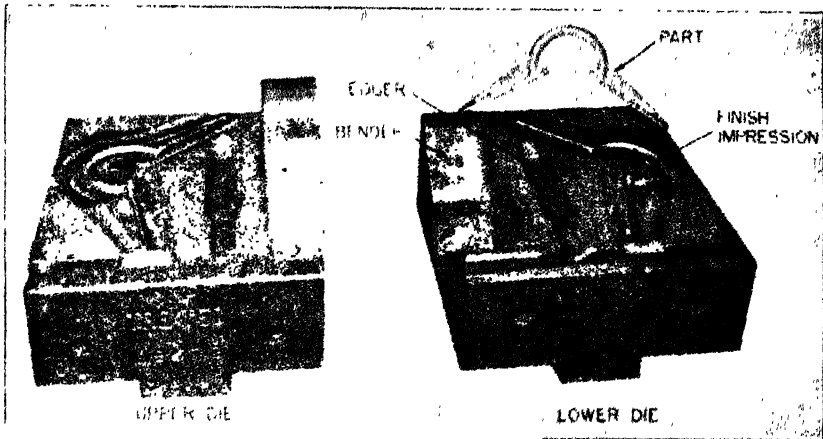
FIG. 18.23. Forging die.

several parts labeled. In this die the stock is first upset on both ends in the edger, than transferred to the bender, where it is made to conform reasonably well to the impression. It is finally brought to the finished shape in the finish impression. Overflow into the gutter (which surrounds the finish impression) is subsequently trimmed in a die conforming to the profile of the forging at its parting line (see Fig. 18.24).

If the shape of the part makes drastic metal flow unavoidable, an intermediate or breakdown impression would be employed. This would forge a partial development of the finished shape and would serve to protect the finish impression from excessive wear. Its smooth contours also would aid in filling deep recesses properly.

In order to prevent overheating of the die and to loosen the scale on the forging, the part should be lifted slightly between blows. This is possible only when sufficient draft has been allowed by the de-

signer (see paragraph 18.10). Lubricant applied to the impression aids in the ejection of the part and in loosening of scale by reducing sticking and by gasifying when in contact with the hot forging. The gas pressure forces the part free of the cavity.

Before describing the operations required to produce some typical drop forgings, drop hammers and their operation will be considered. All drop hammers consist of three essential parts: a hammer or ram, a lifting device, and an anvil. The machines are classed according to their lifting device as steam, air, or board drop hammers.
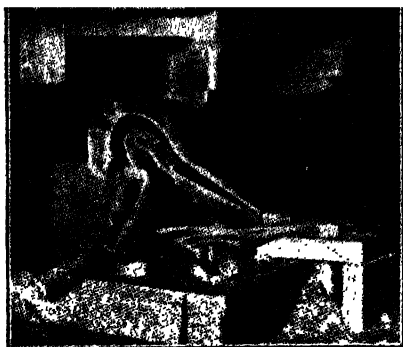
Fig. 18.24. Trimming die for forging made in die shown in Fig. 18.23.

The *board drop hammer*, shown in Fig. 18.25, has boards, usually of maple wood, assembled into the ram by means of wedges. The upper ends of these boards lie between two rollers which are controlled automatically so that when the rolls squeeze against the boards and revolve in opposite directions the ram is lifted. At a predetermined height, the rolls are automatically spread apart. Before the ram falls, wedges lock in against the boards. When the operator wishes to strike a blow, he presses a treadle and the connecting linkage releases the wedges.

This type of hammer is generally driven directly by electric motors and requires no steam or high-pressure air. Ratings are given by the weight of the falling parts, and range from 200 lb to 750 lb, with heights of 30 in. for smaller sizes and 60 in. for the larger. It is the least expensive of the three types to operate.

The *steam drop hammer,* Fig. 18.26, has the same essential parts as the board hammer except that a steam cylinder, piston, and rod are substituted for the board lifting mechanism. The steam hammer utilizes the driving effort of the steam both on the lift and on the power stroke, resulting in a faster and more powerful hammer and one that can be better controlled. Because of its higher speed and controlled blow, the steam hammer is superior to the board hammer, where preliminary bending or drawing is required. Steam hammers are available in sizes from 600 lb to 50,000 lb.

The *air hammer* is similar to the steam hammer in operating characteristics and construction. It is adapted to the same classes of work as the steam hammer, is available in the same sizes, and is justified principally by a lower operating cost.

The following typical jobs will serve to illustrate the type of work which is normally done as drop forging work.

Copper-Switch Contact. Fig. 18.27 shows a die for forging copper-switch contacts. Three impressions are shown in this die: (1) the edger, shown at top but located at the operator's right in service (for first upset); (2) the breakdown impression (lower, the partial development of the finished shape); and (3) the finish impression (middle, note gutter around this impression).

Crankshaft. The various steps in forging a single-throw crankshaft are shown in Fig. 18.28. Figs. 18.29 to 18.33 are included to show some of the actual setups. The operations are in order:

(1) Form flange and draw tong hold (Fig. 18.28b and 18.29). Stock is turned in the dies between hammer strokes, to gather flange metal.
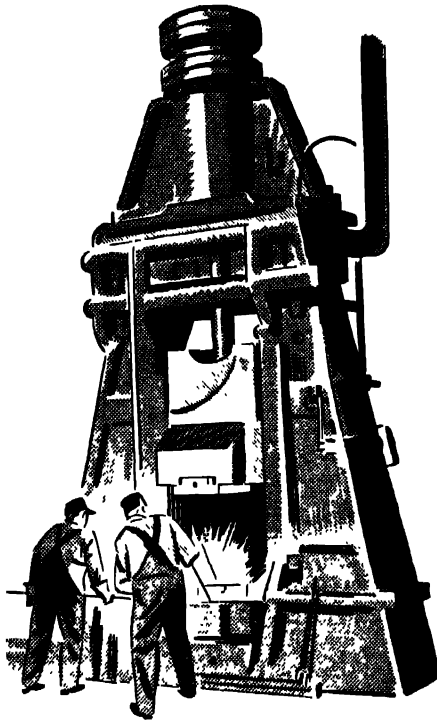
FIG. 18.26. Steam drop hammer. (*Courtesy Drop Forging Association.*)
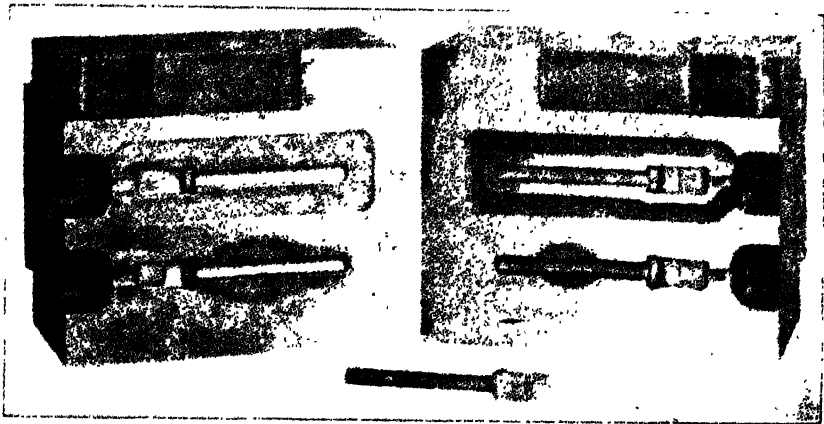
FIG. 18.27. Dies for a copper switch contact. A part made with these dies is shown in the center foreground.

(a) (b) (c) (d) (e) (f)
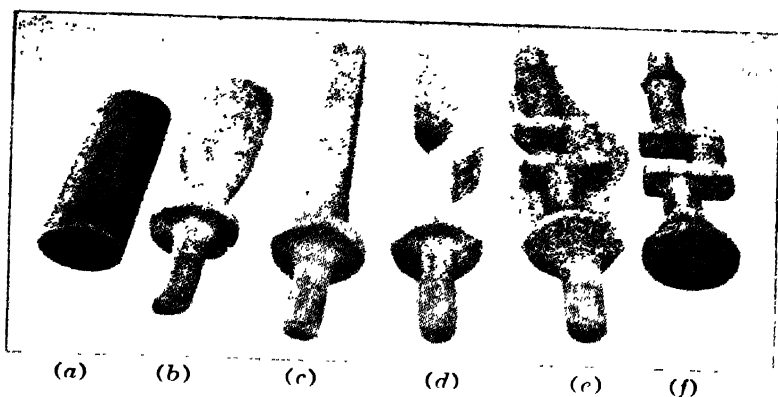
FIG. 18.28 Steps in forging a single-throw crankshaft.

FIG. 18.29. Forming tong hold and flange.
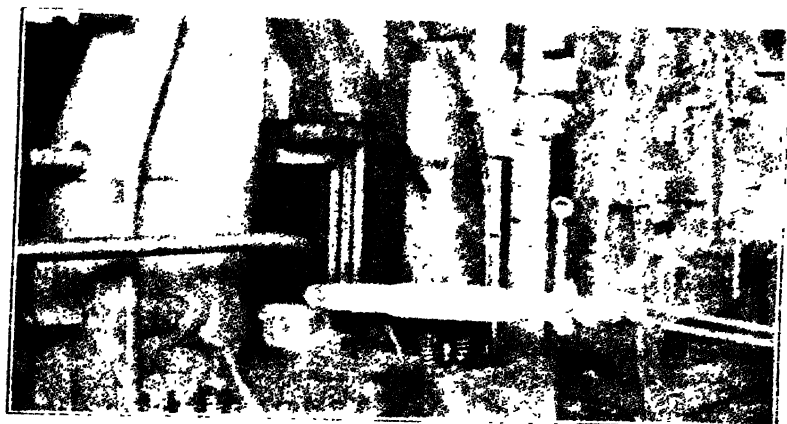
FIG. 18.30. Drawing and flattening operation.

(2) Flatten (Fig. 18.28c and 18.30). Done between plain flat dies.

(3) Bend (Fig. 18.28d and 18.31). Done to make stock fit into die impressions.

(4) Forge in crankshaft impression (Fig. 18.28e and 18.32). Bent stock is forged until chilled flash prevents further metal flow.

(5) Trim flash (Fig. 18.28f and 18.33).

(6) Reheat.

(7) Forge again in crankshaft impression (Figs. 18.28e and 18.32).

Continue if necessary until shaft is reduced to drawing size.

(8) Trim flash again (Fig. 18.28f and 18.33).

(9) Restrike in crankshaft impression for final straightening and sizing.

(10) Saw off tong hold.

(11) Heat treat.

(12) Shot blast.

In the forging of a shaft of this type several hammers may be necessary. Where possible, all dies are set at one time, the forging passing from furnace to hammer, back to the furnace and to the next hammer, thus saving the heat left after each preceding operation.

18.10 DESIGN PRINCIPLES FOR DROP FORGINGS

Certain principles relating to drop forgings that have been brought out directly or indirectly may be summarized as follows:

(1) The sections of the forging should be balanced about the parting line. Where this is impossible, design for the simplest irregular parting line which approaches a balanced condition.

(2) Generous inside fillets and external radii should be allowed. Minimum radii, when required, should be $\frac{3}{64}$ in. for small parts and $\frac{1}{8}$ in. for large work.

(3) Sufficient draft should be allowed for easy removal of the part. For the board hammer, 7° on external surfaces and 10° on internal ones are preferred, but modern machines can produce 5°. Steam- and air-drop hammers normally require $5\frac{1}{2}$° and 7° respectively with $1\frac{1}{2}$° minimum for new machines.

(4) Changes in section must be gradual and thin isolated sections should be avoided. Sections $\frac{3}{32}$ in. thick can be forged in small parts but $\frac{1}{8}$ in. is preferred.

(5) Deep pockets and recesses should be avoided. External bosses may have height equal to $\frac{2}{3}$ their diameter.
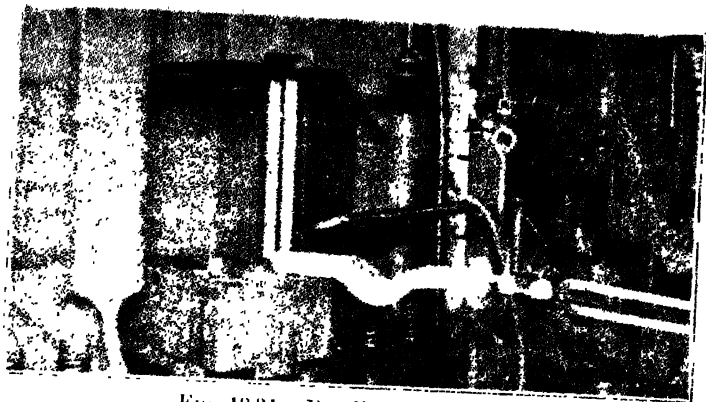
Fig. 18 31. Bending operation.

Fig 18 32. Finish forging operatic
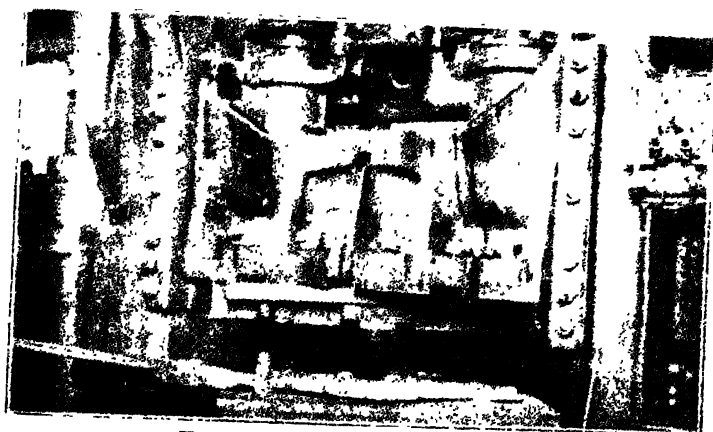
Fig. 18.33. Trimming operation.

(6) Holes in two nonparallel axes prevent removal of parts from the dies.

(7) Machining allowance may be as little as $\frac{1}{32}$ in. on small parts to $\frac{5}{16}$ in. for large parts.

(8) Scale on steel parts should be cleaned by blasting, rather than pickling, when the part will be subject to fatigue loads.

(9) Coining of finished dimensions can be held to ± 0.001 in. The forging is given an allowance of 0.015 in. for a $\frac{1}{2}$-in. dimension and 0.010 in. per in. for larger diameters prior to coining.

(10) Tolerances depend on size and are larger across the parting line than parallel to it. Minimum commercial tolerances across the parting line are $^{+0.024}_{-0.008}$ on small parts, $^{+0.036}_{-0.012}$ for 1-lb forgings, and $^{+0.074}_{-0.058}$ for 100-lb forgings. Close tolerances are half these values.

18.11 FORGING MACHINE WORK

An important development in the field of forging equipment is the forging machine. In it the hot work is held by stationary grips and upset by an upsetting ram, or header. The machine has several grips and several corresponding positions in the header, so that suc-
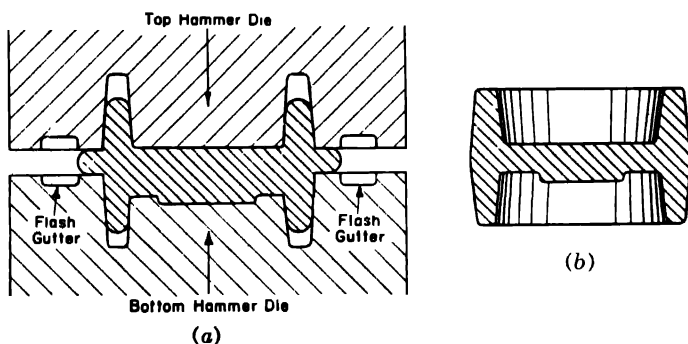
FIG. 18.34. (a) Die forging action; (b) the forged part.

cessive operations may be performed in sequence without requiring reheating between operations. The operation of the forging machine is primarily one of gathering, or upsetting. This is to be compared with the spreading, or flattening, operation of the drop hammer.

Because of the spreading of stock beyond the die impression in drop-hammer work, it is occasionally necessary (for close tolerances) to trim off the flash in order to develop sufficient pressure on the stock to cause it to fill the impression (see Fig. 18.34). The arrangement of

the dies in a forging machine allows many types of upsets to be confined in the heading tool or between the gripping dies (Fig. 18.35), thus eliminating the intermediate trimming operations. When flash cannot be avoided, it should be located where it can be easily removed by trimming, chipping, or grinding.

The slugs of metal forged to the shape shown in Fig. 18.35*b* are pinched from bar stock by the grip dies as they close, the bar being inserted perpendicular to the plane of the page. After the grip dies

(a)   **(b)**
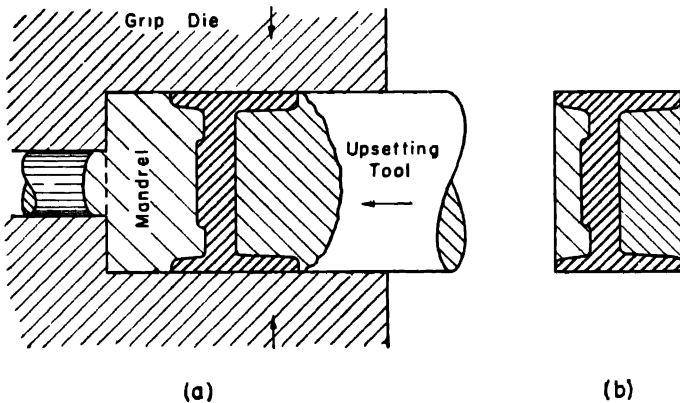
FIG. 18.35. (*a*) Machine forging action; (*b*) The forged part. Compare with Fig. 18.34.

have closed, the upsetting tool rams in, squeezing the metal to the desired shape. The upsetting tool returns, the dies part, the mandrel is pushed out, and the forging is removed from the mandrel. After the mandrel is replaced in the dies, the cycle may be repeated.

18.12   DESIGN PRINCIPLES FOR UPSETTINGS

Three rules which govern the proportions of most upsets made on forging machines are as follows.

(1) *The limiting length of unsupported stock that can be gathered or upset in one blow without injurious buckling is 3 times the diameter of the bar.* As an example (Fig. 18.36*a*), if the diameter of the bar, *d*, to be upset is 1 in., then the length of the unsupported stock, *L*, which can be successfully gathered cannot be more than 3 in. This rule applies to all diameters of stock. On such upsets (Fig. 18.36*b*), the stock will upset uniformly in all directions from the axis of the blank. There will be no serious tendency to upset unevenly. How-

ever, if an effort is made to upset a length of stock longer than 3 diam, the stock will buckle at a point near the middle and result in a flattened bend rather than the uniform upset (Fig. 18.36c) that is desired.

(2) *Lengths of stock more than 3 times the bar diameter can be successfully upset in a cavity with one blow, provided the diameter of.*

(a)

(b)

(c)
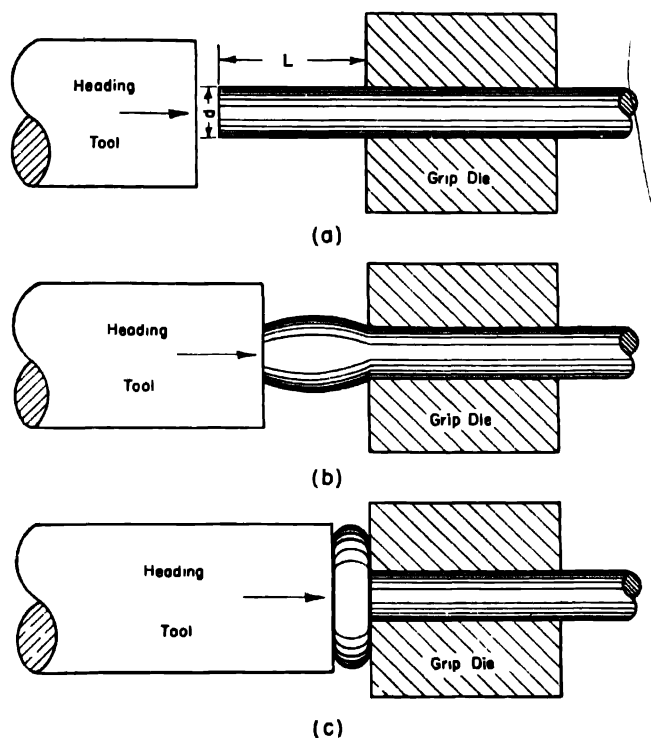
FIG. 18.36. Rule 1: *L* must be no greater than 3*d*.

the cavity is not more than $1\frac{1}{2}$ times the bar diameter. Assuming that the diameter of the bar in Fig. 18.37ā is 1 in. and the length of stock, *L*, to be upset is 6 in., the diameter of the cavity in the die must not be more than $1\frac{1}{2}$ in. When upsetting begins, as in Fig. 18.37b, the stock will at once buckle, but because of the limited diameter of the cavity, the stock soon comes in contact with the sides of the die. This prevents further buckling at that point, hence additional buckling must take place at some other point. As the header advances, the stock will finally upset and fill the impression. If rule

2 is violated, fold defects are likely to occur in the upset where bending has progressed too far before upsetting began.

The practical application of this principle is in the gathering of large amounts of stock by repeating the upsetting operation, as indi-
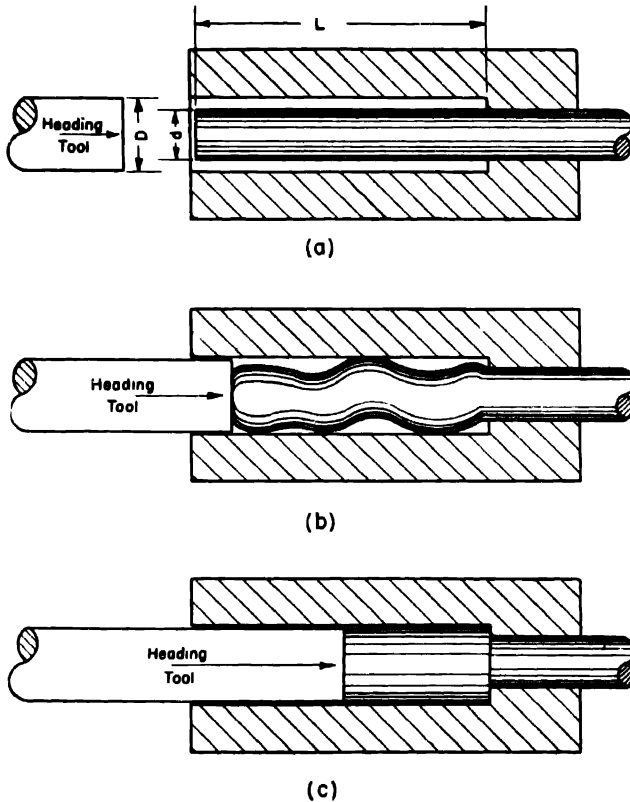
Fig. 18.37. Rule 2: D must be no greater than $1\frac{1}{2}d$.

cated in Fig. 18.38. In the first or top impression, the diameter D_1, of the recess in the die is not more than $1\frac{1}{2}$ times the diameter of the bar, d. In the second impression, the diameter of the recess, D_2, is not more than $1\frac{1}{2}$ times the diameter of the previous upset, D_1. In the last impression, the length of the upset, L_2, is well within the limit of rule 1, regarding the length of unsupported stock, so that no limit need be put on the diameter, D_3, of the last impression.

(3) *In an upset requiring stock more than 3 diam in length and in which the diameter of the upset is $1\frac{1}{2}$ times the bar diameter, the*

amount of the unsupported stock beyond the face of the die must not exceed 1 diameter of the stock. For example, if the stock to be upset is 1 in. in diam by 6 in. in length (Fig. 18.39a) and the diameter

(a)

(b)

(c)
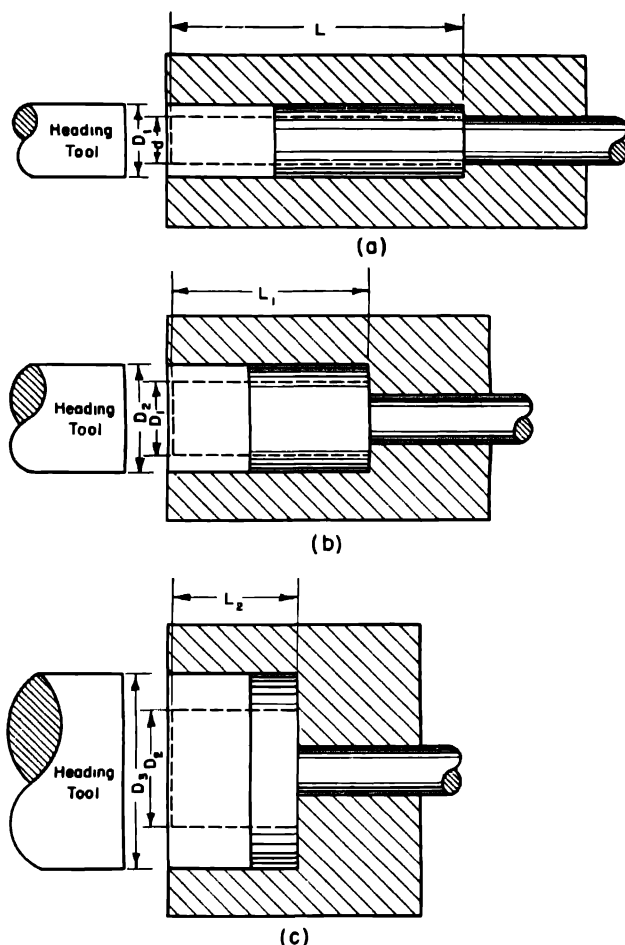
FIG. 18.38. Successive upsetting operations.

of the hole in the die is 1½ in., then the amount of stock, E, extending beyond the face of the die must not be more than 1 in. However, if the diameter of the cavity (which may be in the heading tool or the die, Fig. 18.39b and 18.39c) is reduced below one and one half diameters, the length of the unsupported stock beyond the face of the die can be increased. In Fig. 18.39b the diameter of the cavity, D', is

one and one fourth times the stock diameter, d, so the amount of stock beyond the face of the die, E', has been increased to $1\frac{1}{2}$ times the bar
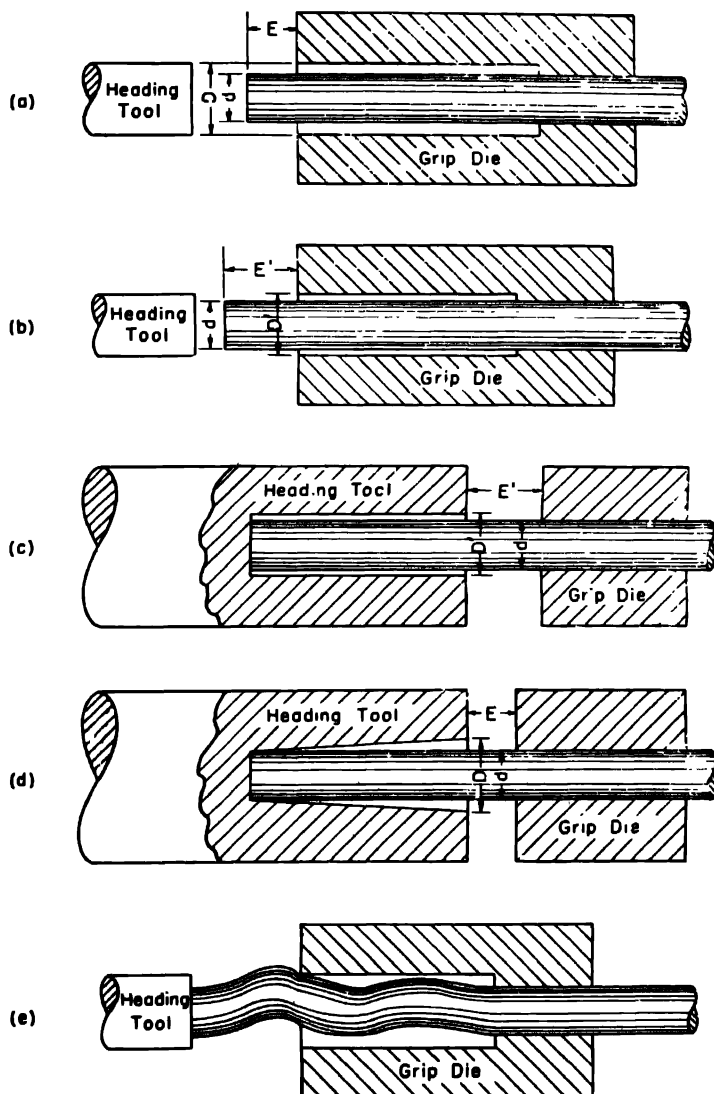
FIG. 18.39.   Rule 3: E must be no greater than d if $D = 1\frac{1}{2}d$.

diameter.   This rule applies to cases where the upsetting takes place in either straight or tapered cavities as shown in Fig. 18.39c and 18.39d.   Should a greater amount of stock extend beyond the face

of the dies, it is likely to buckle outside of the cavity as shown in Fig. 18.39*e*.

Draft. In forging machine work, as in drop forging, draft must be allowed on the faces parallel to the header motion. In general, from 3 to 5° is allowed, but where pockets are wide and thicknesses small it may be reduced to one degree or less.

18.13 FORGING SPECIFICATIONS

It is customary in design of forgings to specify one or more of the following acceptance tests to insure part quality before passing the part or parts into production.

1. Chemical analysis per material specified selected usually midway between surface and center.

2. Mechanical properties such as tensile strength, yield strength, impact strength, hardness, 180° bend test, or fatigue strength on cupons cut parallel and perpendicular to the grain flow.

3. Corrosion tests where applicable.

4. Visual tests such as macroetch, macroexamination, sulfur printing for steel, and magnetic particle or zyglo testing for surface or subsurface cracks.

Heat treatments specified for forgings depend on the material and the end use of the product. As discussed in Chapter 17, few steel forgings are used in the annealed or normalized state. The majority are given normalizing, quenching, and tempering treatments. Hardness of 250 to 283 Brinell is usually specified for machinability. For forgings to be finished to very close tolerances a schedule of normalize, anneal, rough machine, quench, temper, and finish machine, or another of normalize, quench, temper, semifinish machine, stress-relief anneal, and finish machine are usually used, the latter being preferred for the highest accuracy.

18.14 HOT PRESSING

This process, sometimes termed press forging, is one of the more recent developments in impression die forging for carbon steel, alloy steel, and stainless steel, as well as for aluminum, magnesium, and copper alloys.

Presses used are of two general types, but both produce a sustained pressure at relatively slower ram travel than for the other processes. Mechanical types are available in ratings from 500 tons to 6000 tons, and 10,000 tons seems possible. Operating speed is from 30 to 120 strokes per min, the higher speed probably imparting some im-

pact pressure. Hydraulic types are rated from 250 tons to 6000 tons in standard sizes, and special ones have been built to 18,000 tons. Free travel of the ram ranges from 100 to 1000 in. per min, and is from 25 to 300 in. per min at full forging pressure. The impression dies used may be similar to those used for drop forging, sometimes contain edging and fullering sections. The latter are not used to the same degree as in drop forging, and the usual steps consist only of flattening or pancaking of up-ended stock, blocking, and finish impression forging. Often, preshaped blanks from a drop hammer or rolling mill are used. Pairing of parts is preferred for unsymmetrical forgings to balance pressures on the ram and dies.

Hot-pressed parts can be made more accurately, require less draft, and have fewer design limitations than drop forgings, though their size may be somewhat more limited. For such shapes as can be handled in one heat, where production is high enough to justify the forging-die cost, and where the accuracy and tolerances of drop forging are satisfactory, drop forgings will be less expensive than hot pressed parts.

18.15 HOT-PRESSURE WELDING

The production of butt-welded and lap-welded pipe are applications of hot-pressure welding, but the use of this process for other shapes and materials is only of recent origin. Theoretically, there is no limit to the similar and dissimilar joints that can be made. Bonding of two materials is brought about by application of high pressure and production of mutual deformation at temperatures below the melting range of either. It is probable that bonding results from interlocking of the atoms of each piece with some additional interlocking introduced by diffusion. Other names given this process, solid-phase welding, recrystallization welding, and forge welding, are indicative of this action.

The largest application of the method is in the preparation of laminated or clad metals, particularly dissimilar combinations. These range from steel with coatings of copper, monel, nickel, and stainless steel, to most of the nonferrous metals, some with rare metal coatings, suited to bimetallic thermostat elements, electrical contacts, and special service chemical ware.

A growing application in industrial fabrication is the joining of sheet and strip, bar, and tubing, usually of similar metals, to form products in competition with other methods. One such application is the production of all-aluminum capacitor containers. Problems

involved are method of assuring clean mating surfaces at time of joining, application of heat to the contact surfaces, and design for thickness reductions (up to 70 per cent) required by the process to assure intimate metal to metal contact. This field gives promise of important, though specialized, applications as the technique is further developed.

18.16 CONCLUSIONS

Forging, as a manufacturing process, offers many advantages to both the engineer and the factory man. Among these advantages are: (1) equal or greater strength at lower unit weight, compared to castings or fabricated parts; (2) greater consistency of performance than is possible with castings; (3) minimum of surplus material to be removed by machining.

In addition, a comparison with castings shows that drop forgings can be made to closer tolerances, and an excellent surface may be had even on unfinished portions. On the other hand, dies initially cost more than patterns, and intricate shapes may not be forgeable though they could be cast. Generally speaking, the costs of drop forgings and castings in carbon or alloy steel are comparable if composition is the same for each, and if sufficiently large lots are required. Cost, however, is not usually the deciding factor in the selection of these processes.

On the foregoing pages only the general principles and methods of forging have been covered. It should be borne in mind that use of special materials, equipment, or unusual skill will permit different shapes or tolerances to be satisfactorily met.

7. Name the three types of drop-forging hammers.

8. In drop forging, why is a breakdown impression sometimes used in the dies?

9. Name four principles that are normally considered good practice in the design of drop forgings.

10. What type of forging is done on the forging machine? What three rules govern the proportions of parts for upsetting on the forging machine?

11. What are the general advantages of forging as a manufacturing process?

19 COLD-WORKING PROCESSES

by E. W. ERNST *

19.1 INTRODUCTION

The working of metals at temperatures below their recrystallization temperatures is defined as *cold working*. Sometimes this working temperature is well above room conditions as in cold finishing of hot-rolled mill products. Most of the cold-working processes, however, are performed at room temperature. Handling of heated material and use of soaking pits and furnaces are thereby avoided, and speedier production results.

Cold finishing of mill products, such as plate, sheet, tube, and bar, is performed for the properties it imparts to the material. For example, a cold pass of 0.5 or 1 per cent reduction eliminates formation of stretcher strains in subsequent die forming of low-carbon steel. Such cold passes also produce, with intermediate pickling, an improved surface finish and closer dimensional tolerances. Considerable cold reduction is employed to obtain increased surface strength and hardness through work hardening.

Cold-working processes are used in making end-use products for their economy in producing the desired shapes. When surface finish is important, cold-finished mill material is used as the raw stock. The work hardening which results from these operations often is of secondary importance in use of the part, serving mainly to limit the shapes that can be made. There are many exceptions, however, where the improved strength permits a reduction in size and material requirements. The properties imparted by cold working may thus enhance the economy of these processes for end-use parts.

The cold-finishing operations employed on mill products are similar to the hot-working processes described in Chapter 18. Often they are performed on the same equipment. Such operations will not be repeated in this chapter, which will cover the cold-working processes used particularly for end-use parts. There are a great many varieties

* Major Appliance Div., General Electric Co., Louisville, Ken.

of these operations, and numerous terms having slight shades of meaning have become associated with them. The terms in common use are defined in the following paragraph.

19.2   DEFINITIONS OF COLD-WORKING PROCESSES

Bending. A plastic deformation (exceeding the elastic limit) of a sheet, strip, or bar such as is performed on a hand brake,* in contrast to forming, which is a process accomplishing one or more bends about linear axes by making the metal conform to a die shape. The inner radius of curvature is generally specified.

Blanking. A press operation cutting the outside contour of a stamping. Cutting inside contours (i.e., holes and slots) is called piercing.

Broaching. Consecutive shearing of a hole or contour by a series of stepped cutting edges similar to a saw. Generally considered a machining operation (see Chapter 21), but used in slow-acting presses for accurate sizing of holes or contours, such as gear teeth and keyways.

Burnishing. A smoothing, polishing operation accomplished by compression and/or friction; e.g., shaved blanks polished and sized by being forced through an opening having sides tapered slightly inward.

Coining. The compressive cold sizing of a metal used to obtain a smooth finish, close tolerance, or fine detail at less cost than machining.

Cold Rolling. A drawing operation between rolls (no torque applied to rolls) performed below the recrystallization temperature, achieving smaller size, closer tolerance, increased hardness, and higher tensile strength.

Crimping. Producing flutes or corrugations. Often used to gather metal as for stovepipe joints.

Cutoff. An operation that shears a stamping from a strip or bar.

Dinking. Contour cutting and/or piercing by pressing a sharp, thin steel edge through sheet material lying on a flat hard wood platen. Rubber, leather, fiber, paper, felt, etc., may be blanked this way.

Drawing. A stretching process. In tube, rod, or wire drawing the metal is pulled through a die. In cup, shell, or deep drawing the bottom is pressed into a die and the walls are pulled in, hence the name.

Embossing. A shallow drawing operation rarely over 3 thicknesses of the metal deep. Raised letters are often embossed in thin metal strip.

* A device which clamps the material along one side of the bending line and lifts it along the other side, forcing it to bend along the edge of the clamp.

Extrusion. Causing metal to flow through a shaped opening in a die to impart that shape to the metal.

Flanging. Any process producing a flange. A flange may be drawn on a shell, in which case crumpling is prevented by a flange clamp. A tube may be flanged, in which case the end of the tube is stretched and thinned as it is flared out. Wide flanges must be drawn; they cannot be flared.

Forming. See Bending. Forming is often combined with other stamping operations, e.g., piercing, notching, cutoff, etc.

Heading. A metal-gathering, or upsetting, operation so named because it was originally used only for production of screw and rivet heads. Heading is now used to produce a wide variety of different shapes, but the term is generally applied only to cold upsetting.

Knurling. A cold-working process in which a series of sharp serrations on a hardened steel roller are pressed into the material being knurled. Used principally to roughen surfaces for thumb screws, handwheels, etc. The operation usually is performed on lathes or screw machines.

Lancing. A special form of piercing in which the entire contour is not cut, the blanked material remaining as a tab.

Piercing. See Blanking.

Punching. See Stamping.

Riveting. A hammering operation in which the end of a metal pin (i.e., a rod or rivet) is pressed over or spread out. It may be either a hot- or cold-working process.

Roll Forming. Passing strip stock between driven rollers that form the strip to the shape desired.

Roll Threading. A method of threading a part by pressing and rolling between serrated dies.

Seaming. The bending and flattening of an interlocking fold, e.g., a stovepipe seam.

Shaving. A refinishing operation that cuts a small amount of material from the edge of a stamping to gain finish, accuracy, and/or a square edge.

Shearing. Term applied to cutting in a line by two opposed blades, somewhat in the manner of the ordinary household shears.

Shell Drawing. See Drawing.

Spinning. A technique of kneading sheet material about a rotating form into a desired circular shape.

Stamping. ·A general term covering all punch-press operations, including the squeezing operations, such as embossing, coining, swedg-

ing, forming, and shallow drawing, as well as the cutting operations, such as blanking, lancing, and piercing. A part from punch-press operations is also known generally as a stamping.

Swaging. A hot or cold hammering process in which the material is not fully confined. For example, a rod or tube may be reduced in diameter or tapered by swaging, i.e., repetitive blows between proper dies. Swaging machines rapidly open and close die halves (or quarters) on the work as it is fed between them. The dies themselves rotate.

Swedging. A cold die forging operation in which the metal is confined and made to flow plastically into the punch and/or die impressions. Used extensively in displacing metal around a hole to obtain sufficient thickness in thin stock for threading. Coining is also a swedging operation.

Trimming. Cutting away excess material left from previous operations.

Upsetting. The gathering of metal in a rod or bar to achieve a larger cross section. Performed either as a hot- or cold-working operation. See Heading.

Wire Drawing. See Drawing.

Press-Working Operations

19.3 PRESS WORKING

The equipment used for cold-working processes consists of a wide variety of presses suited to many types of operations, and of other types of machines developed for particular classes of work. It is convenient to group the general press-working operations under this heading. The other operations will be considered later.

The variety of available processes, their size range, the operations they perform, and their applications are tabulated in Table 19.1. A wide variety of operations can be accommodated on many of the presses, but when the design may be more economically produced on a specialized press, the engineer, planner, and tool designer should study the economies of tooling such presses, or introduce separate operations on more standard presses of the required size.

Die construction and the workability of materials influence the design of parts to be made by press-working operations. The factors involved are discussed in the following paragraphs.

Table 19.1 Stamping and Drawing Presses *

Machine	Size	Operations	Features	Uses
Foot press	Small sizes only	Small work—single small holes, light stampings, embossing	Hand fed; may have adjustable bed or horn to accommodate large work	Jewelry, buttons, silverware, radio parts, etc.
Bench press	1000 pounds to 12 tons	Embossing, stamping, etc., upon light material	May have roll feed, ratchet dials, magazines, etc.	Watch parts, novelties, jewelry, etc.
Inclinable press	4 to 90 tons	Blanking, bending, stamping, forming, assembling	Inclined from vertical to 45° backward; may have drawing attachments	For light sheet metal
Open-back gap press	1 to 225 tons	Punching, shearing, cutting-out, trimming, forming, etc.	Ram driven by cam or eccentric	Automobile parts, etc., for large or irregular work
End-wheel gap press	Small to 50 tons	Blanking, forming, notching, piercing, cutting	Flywheel at rear and crankshaft at right angles to bed	For work with long, narrow strips of metal
Deep-gap punch press	Medium sizes	Punching	Deep clearance in back frame	For wide sheets
Horning press	10 to 100 tons	Forming, stamping, blanking, wiring, punching, riveting	Horn bolted to frame; may have swinging table also	For hollow cylindrical work, as steel drums, etc.
Double-crank over-hanging press	Small	Blanking, cutting, piercing	Usually automatic or semiautomatic feed—over-hanging frame gives large die space—flywheel—or gear-driven	For large, light sheet metal
Notching press	Small to medium	Cutting slots in edges of usually circular work	Usually short stroke machine, with work driven by rocker arm—450–650 strokes per min	Notching motor laminations
Single- and double-action presses	Heavy	Shaping, blanking, forming, etc.	Frame consisting of a base, a crown, and two uprights tied together with steel tie rods	Heavy stock
Arch press	Light	Cutting, trimming, shaping, blanking	Offers large bed area	For light, large-area sheet metal
Double-crank straight-side press	To 2000 tons	Punching, cutting, bending, blanking, shaping	Slide often counter-balanced by air cylinder—flywheel or geared	Wide variety of uses in many sizes
Four-point suspension press	100 to 1500 tons	For large-scale deep drawing, etc.	Four corners of slide suspended, giving even pressure on work	Automobile body tops, etc.

Press	Capacity	Operations	Characteristics	Applications
Knuckle-joint press	25 to 250 tons	Coining, upsetting, swaging, embossing, extrusion	Knuckle-joint operating slide makes short stroke necessary	Coining money, light to medium thickness metals
Straight-side high-speed press	10 to 400 tons	Blanking, stamping, etc.	Heavy construction to eliminate vibration—high speed roll feed, and scrap cutter, variable speed motor—about 400 rpm	For high production with comparatively light metal
Dieing machine	Small	Progressive die operation, etc.	Ram operated with a pulling stroke rather than a thrust, by vertical rods passing down through bed—about 350 strokes per min	Electrical appliance parts, small automobile parts, etc.
Oscillating-die press	Small	Blanking, cutting, etc.	Die moves horizontally back and forth; strip fed through continuously. About 1000 strokes per min	Small parts of light-gage material
Multi-slide machine	Small	Combination of operations, as blanking, forming, bending, etc.	As many as 8 operations may be performed in succession by the different slides. Very accurate feeds. To 300 pieces per min	Operations upon light-gage metal
Double-action press	Small, medium or large	Blanking, drawing, etc.	Stock is successively blanked and worked by an outer and an inner ram	Applications requiring two related operations
Pillar press	70 to 250 tons	Blanking, shaping, trimming, etc.	Subpress dies may be attached to the face of the ram for close-tolerance work	Light- to medium-gage work
Toggle press	Small	Usually double action, in which the outer slide holds the blank, and the punch, or drawing ram, forms the cup		Kitchenware
Hydraulic press	To 1000 tons	High-speed pumping units can give this type of press operating speeds comparable to other large presses		Largest size of work
Horizontal draw press	Small to medium	Shell may be pushed through die for redrawing, or knockouts and stripper plates provided if shouldered		For cylindrical shells
Multiple-plunger eyelet machine	Small	Successive draws made by a row of plungers, the work transferred from station to station by finger conveyors		Light-gage shells
Rack-and-pinion deep-drawing press	10 to 30 tons	For long uniform redrawing operations with accurate length of stroke		Cylindrical shells

* Compiled by Kenneth Rose, Engineering editor, *Materials & Methods*, November 1943.

19.4 PUNCH AND DIE TERMINOLOGY

The term "die" is often applied to an entire press tool, including both upper and lower members. The names punch and die are used to designate parts or sections of a complete die (see Fig. 19.1). When
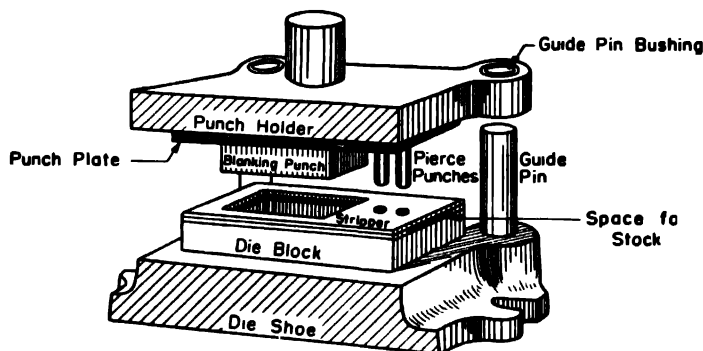
FIG. 19.1. Conventional die set.

the name, die, is applied to a part of a press tool, it refers ordinarily to the member that has an opening or cavity for blanking, drawing, or forming.

A "punch" is that part of a press tool that enters into the opening or cavity formed in the die section. The punch usually is the upper member, being attached to the press slide or ram.

A few notable exceptions to this conventional arrangement can be pointed out. Certain press tools are of inverted design and have the die affixed to the ram. Some kinds of dies have a blanking punch on the lower member in which there are holes to receive piercing punches from the upper member. Thus, one member may perform functions of both punch and die, and the location of a member cannot always be considered the criterion of function.

19.5 DIE CLASSIFICATION

Press tools can be classified as cutting dies, noncutting dies, or combination dies. These may be subdivided as single-station dies or progressive dies. Some of the types of press tools in use are listed under these divisions in Table 19.2.

19.6 SINGLE-STATION CUTTING DIES

The single-station dies consist of a male and a female part operating on a stamping at one stroke of the press and at one positioning

Table 19.2   Classification of Press Tools

	Cutting Dies	Noncutting Dies	Combination Dies
Single-station dies	Plain piercing Plain blanking Compound blanking Comp. pierce and blank Shaving Trimming Trim and pierce Cutting-off Dinking Subpress Horning Broaching Indexing Lancing Notching	Straightening Flattening Upsetting Bending Forming Burnishing Coining Swedging Extruding Expanding Assembling Drawing Embossing	Comp. blank and draw Cutoff and form Blank and emboss Pierce and swedge
Progressive dies	Pierce and blank Notch and blank Notch and cutoff		Pierce blank and form Blank and form Trim cutoff and form Pierce trim cutoff and form

of the material. Such operations as blanking, broaching, cutting off, dinking, piercing, shaving, and trimming are performed on suitable dies of this type. Other single-station cutting dies include the following.

Compound Blanking Dies. A compound die usually has the die or female part on the top holder, and the punch in the lower holder. The inside of the die portion is fitted with a "knockout" plate operated by springs or by a mechanical knockout, which operates at the top of the press stroke, to eject the blank after the ram of the press has ascended. The punch on the bottom holder is surrounded by a "stripper" which pushes the sheet back to the top surface of the punch after the die leaves it. Compound dies are used in blanking to maintain flatness and accuracy.

Compound Pierce and Blank Dies. A compound pierce and blank die carries both male and female parts on both moving and stationary parts of the die. The upper, or moving, portion carries the die part for cutting the outside contour of the stamping.

Trim and Pierce Dies. These dies combine the functions of both named tools.

Subpress Dies. A self-contained unit with four guide pins or other means for aligning punch and die is called a subpress die. This tool is thus not dependent upon the alignment of the ram of the press for maintenance of clearance for its punch and die. The punch holder is not rigidly clamped to the ram of the press.

Horning Dies. These dies are built in the form of a horn or projecting part, for instance, for piercing a cylindrical object. The horn fits inside the cylinder and carries the die.

Slot Dies. These are used with index fixtures to produce a series of slots or holes in a circular punching by piercing one or more holes, then indexing to the next location.

19.7 NONCUTTING SINGLE STATION DIES

In one classification are dies suitable for bending, burnishing, coining, drawing, forming, swaging, and upsetting. Other dies in this class for other operations are as follows:

Straightening and Flattening Dies. Generally, these are two flat or stippled plates between which the stamping is flattened with great pressure.

Extruding Dies. Extruding dies are used to cold work materials by exerting sufficient pressure on the metal to cause it to flow through prepared openings that give the metal the desired shape. This process is usually used to produce rods or tubes and is generally restricted to the softer metals. Current developments indicate that steel may be successfully extruded. This success is due mainly to the use of lubricants that will withstand the very high pressures encountered.

Hot-Forging and Cold-Forging Dies. These dies are for working metal hot or cold under drop hammers (see Chapter 18).

Expanding Dies. Tubular parts are expanded by mechanical or other means in these dies.

Hydrostatic Dies. These dies are operated by liquid pressure, usually for expanding purposes.

Assembling Dies. Dies used in assembling parts for press fitting, riveting, clamping, seaming, staking, curling, ironing, crimping, etc., are assembling dies.

Reverse Drawing Dies. These dies are used to draw a shell inside out. This method is often used when the required reduction in shell diameter is at, or near, the practical limit for a single drawing operation.

19.8   COMBINATION SINGLE-STATION DIES

These dies may perform cutting or noncutting functions in one station.   An example is a compound blank and draw die.   The blank is first cut between the blank punch on one tool portion and the blank ring on the other.   Then the blank punch functions as a clamp ring to prevent wrinkles in the part, which is drawn down into the draw die by the draw punch.

19.9   PROGRESSIVE DIES

Progressive dies may perform both cutting and noncutting functions in sequence at different stations of the die, each station or stop performing its single operation on the stamping for each stroke of the
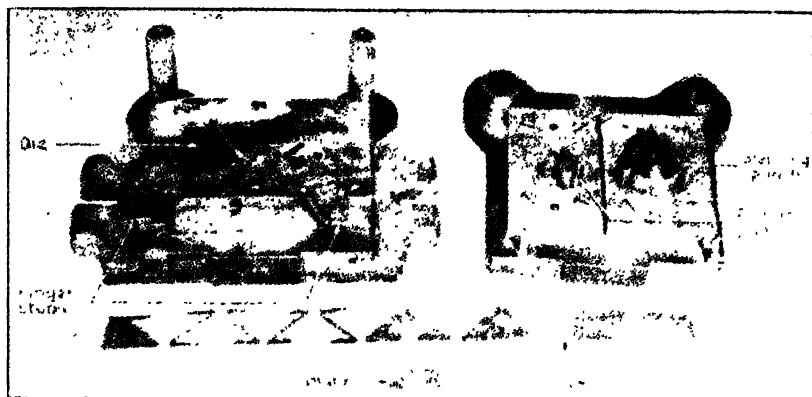
Fig. 19.2.   Progressive pierce and blank die.   Note how stock is run through dies a second time to utilize all of stock.

press.   Under this classification are listed plain pierce and blank dies; pierce, blank, and form; compound pierce and blank; blank and form; blank and draw; trim, cutoff, and form; pierce, trim, cutoff, and form.   All the above are multiple-operation dies, the functions of which are apparent from their names.   They produce a complete stamping from strip or sheet metal at each stroke of the press.

Figures 19.2 and 19.3 illustrate progressive dies.   The finger stops (in Fig. 19.2) and the gages (in Fig. 19.3) regulate the positioning of the stock before each stroke of the press.

19.10   TYPES OF DIE CONSTRUCTION

The dies used for producing stampings may be divided roughly into eight types, as follows:
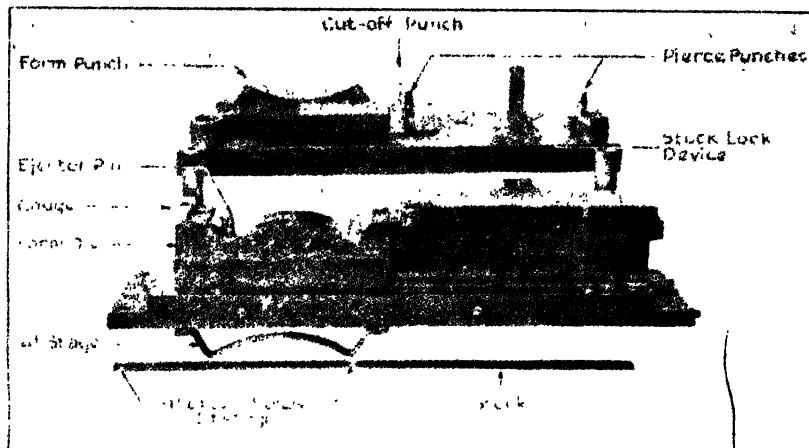
FIG. 19.3. Progressive pierce, cutoff, and form die for refrigerating-machine bracket.

(1) *Carbide Dies.* Dies made of carbide are used primarily for cutting dies for extremely high production, or for quantities in excess of 6 million pieces. They cost about 3 times as much to build as a conventional Class A die. Carbide inserts are also used at wear points on high production forming dies for materials of abrasive nature, such as stainless steels.

(2) *Conventional Dies—Class A.* This type represents the best steel die that can be built for high production, quantities of 1 million pieces and over. It is applicable to cutting, noncutting, and combination dies. Best types and grades of tool steels and other materials are used. Wear points and delicate sections are designed to facilitate adjustment or replacement. A die of this type is shown in Fig. 19.1.

(3) *Conventional Dies—Class B.* This type is used for quantities up to 1 million pieces. General design and application are similar to Class A dies, except that cheaper tool steels and other materials may be used. Both punch and die sections usually are made of thinner materials than Class A dies. They can be built for about ½ the cost of Class A dies.

(4) *Flame-Hardened Dies.* These dies are used for cutting dies where the total production does not exceed 500,000 pieces. They are constructed similar to Class B dies, except that thinner material is used for punch and die sections and only the cutting edges are hardened by the flame-hardening process. These dies are made of ⅜-in. thick tool steel as compared to 1-in. thick for Class B dies, and up to 2¼-in. thick for Class A dies, and cost about ⅓ that of Class A dies.

(5) *Template Dies.* Dies of this type are used for cutting dies where the total production does not exceed 20,000 pieces. They are similar to conventional dies except that punch and die blocks are made from thin tool steel (1/16-in. minimum), and flame hardened at the cutting edges only. The blocks are mounted on special universal punch and die holders for operation. They can be built for about one-eighth the cost of Class *A* dies.
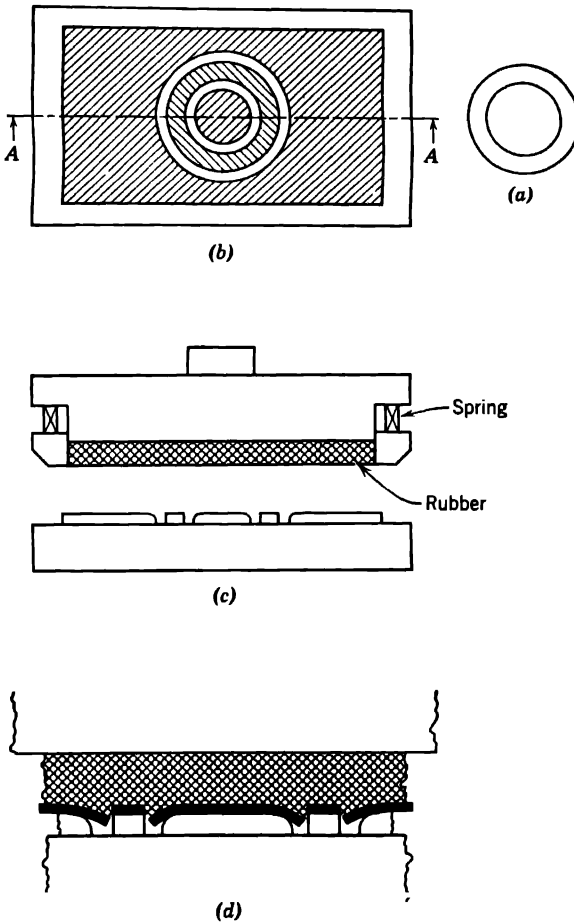
FIG. 19.4. Rubber die used for piercing and blanking. (*a*) Part to be produced. (*b*) Plan view of die. (*c*) Section *A-A* of die in view (*b*). (*d*) Enlarged section *A-A* with die in closed position.

(6) *Rubber Dies.* Rubber dies (Fig. 19.4) are used for low-production jobs up to 10,000 pieces with thin material. In cutting ap-

plications, the lower member consists of a thin, sharp-edged, tool-steel template of the same shape as the part being produced. A second template of the same thickness and having rounded edges surrounds the first template, leaving a narrow space between. These templates are soldered to a plate or die holder. The upper member consists of a piece of rubber backed by a steel punch and confined by a spring-backed steel ring. The same upper member is used for all dies. The rubber exerts sufficient pressure to force the material into the opening around the template until it is cut by the sharp edge. Such dies cost $\frac{1}{16}$ as much as Class A dies.
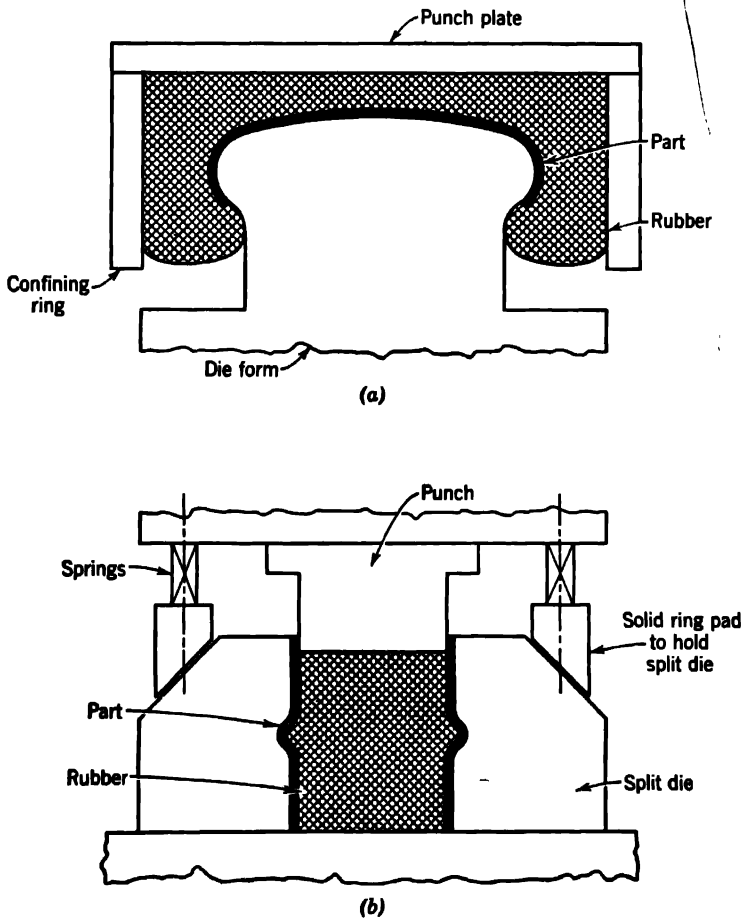
Fig. 19.5. Rubber dies for producing (a) external and (b) internal undercut forms.

Rubber die members are also useful in producing external and internal undercut forms as shown in Fig. 19.5a and b. The die form must be so designed that the part may be removed after forming. The form shown in Fig. 19.5a, if of uniform width or tapered in one direction, is removed by sliding off the die form. The form in Fig. 19.5b requires a split outer die. Rubber die forming, also called the Guerin process, is widely used in the aircraft industry, where low tooling cost for low production rates is especially advantageous. Zinc, aluminum, wood, and masonite are often used for the die form in making aluminum parts.

(7) *Continental Dies.* Continental dies are of the push-through type illustrated in Fig. 19.6. The stock is first inserted between the
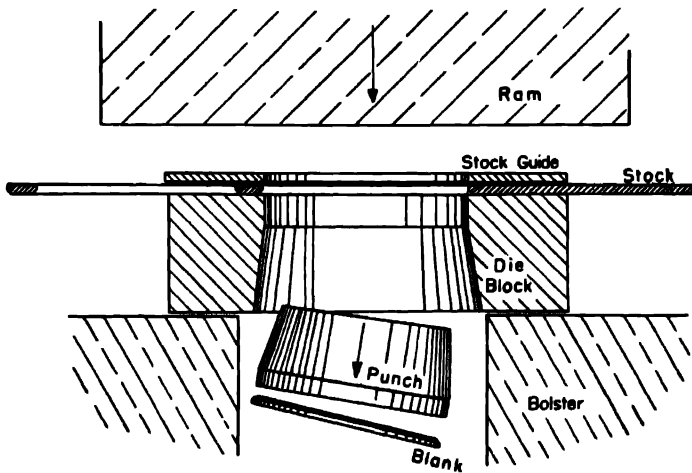
Fig. 19.6. Continental die set.

guide and the die, and a loose punch is then placed in the guide on top of the stock. The ram of the press, striking the punch, pushes both punch and blank through the die.

(8) *Stock Dies.* Stock dies may be defined as dies of standard sizes, catalogued and kept in stock for producing parts with little or no tool cost. They may be used in various combinations and make possible the production of stampings of almost any size or shape.

It is the designer's responsibility to design parts to make use of stock dies when the number of stampings is small enough that the extra labor costs of using them will not exceed the cost of special dies to produce the part. When a greater number of stampings is needed,

or when the shape is not easily produced by stock dies, a special die is built. The tool designer is usually given complete responsibility for the type of construction of such a die. He may choose to make it from a solid block, from separate pieces held as inserts in a cast matrix of a low-melting-point alloy, or from sections screwed to the die holders. The latter method is often desirable for dies to be used for large stampings or for extremely high production, say a million or more pieces. The individual sections can be hardened separately, thus reducing warpage and loss in hardening. They also allow slight readjustment of the die opening to compensate for wear. A top view of a sectionally constructed die is illustrated in Fig. 19.7.
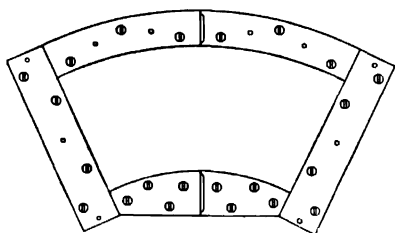
FIG. 19.7. Sectionally constructed die set.

19.11 CUTTING DIE LIFE

Die life, as the term is used in press work, refers to the number of stampings a given die has produced, or is expected to produce, during its normal life. It is affected by many factors, most of which are associated with the design of the dies and their operation in the factory. The factors affecting die life that are directly related to the design of the part are: (a) kind and thickness of the material, (b) quantity of parts per order, and (c) the shape of the part being punched.

As an example of the meaning of die life, consider a die made of water-hardening tool steel, punching 0.019-in. enameled silicon steel such as is used for motor laminations. If such a die set is constructed with a straight punch, a $\frac{1}{8}$-in. straight section, and a $\frac{1}{2}°$ die clearance angle (Fig. 19.8), $\frac{15}{32}$ in. may be ground off both punch and die during resharpening before the burr becomes too great or the stamping becomes oversize. In continuous duty, an average of 90,-000 stampings can be expected per 0.005-in. grind, which means that the die can be ground 94 times before it becomes too large. Thus, a total of 8,460,000 stampings is available from the die, and this number of stampings is termed the *available die life*.

A tapered punch is sometimes used which extends the life of push-back dies by permitting more than twice as much regrinding. The sides of these punches are made to taper outward from the punch
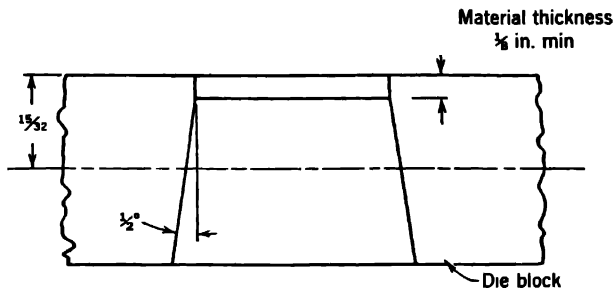
FIG. 19.8. Die clearance and thickness available (to dashed line) for sharpening.

face at the angle of the die clearance taper. Since equal grinds are made on punch and die during resharpening, the correct amount of clearance is maintained, and the set may be resharpened until the stamping exceeds the allowable tolerance permitted on the drawing. Because the punch is tapered, it can enter the die only an amount permitted by the clearance; thus tapered punches can only be used on push-back die sets.

19.12 DESIGN OF BLANK CONTOURS AND CORNERS

Blank shapes should be constructed with true radii, and, in general, rounded corners are preferable to square corners, as it is possible to work out a shape as at B, Fig. 19.9, more readily and cheaply than
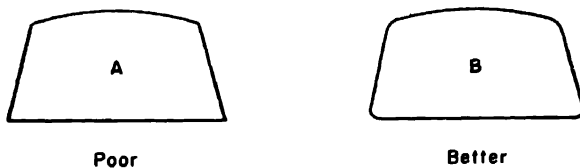
FIG. 19.9. Round corners for blank contours.

a square corner as at A. The rounded corner can be machined complete on a Keller die-sinking machine without subsequent filing or slotting. The Keller machine performs milling and profiling operations automatically with a template as a guide.

Sectional die construction, however, makes square corners preferable (Fig. 19.7). In addition, some blanks which do not need to be cut around their entire periphery can be made from strip stock with a pierce and cutoff die, producing perfectly square corners, with no scrap material on sides or ends (Fig. 19.10a). If a rounded cutoff is needed, one of the two forms shown in Fig. 19.10b is preferred.
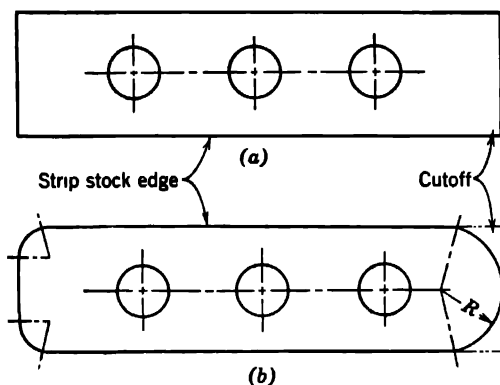
Fig. 19.10. Corners for cutoff dies. (a) Square cutoff. (b) Two types of rounded cutoff which avoid mismatch of cutoff radius with stock edge and give stronger cutoff tool.

19.13 DESIGN OF PROJECTIONS

The width of any projection or slot in a stamping should be at least $1\frac{1}{2}$ times the thickness of the material for $\frac{1}{16}$ in. metal and heavier. For gages lighter than $\frac{1}{16}$ in., these narrow sections should not be less than $\frac{3}{32}$ in. for economical tool manufacture and maintenance (see Fig. 19.11). Projections should be as short as possible, since the longer and narrower they are, the more tendency there is for punch or die breakage in hardening and for excessive wear in use, with consequent high tool cost.

Points as shown in C, Fig. 19.11, should be avoided wherever possible, or made as blunt as design will permit, as these points make uniform hardening difficult and tend to increase die maintenance and decrease die life.

19.14 DESIGN FOR PIERCING

When designing punched parts, care used in deciding the location, shape, size, and dimensions of pierced holes, slots, etc., will greatly reduce tool cost. The following are among the points that should be kept in mind:

Round holes should be used wherever possible in preference to slots or irregular shaped holes as the original tool cost and tool maintenance are less. When oval holes are needed, choice of standard sizes now available in sets should be made if possible.

The diameter or least dimension of any hole should not be less than the material thickness and not less than 0.030 in. in any case. It is

possible to punch holes of smaller dimensions than the material thickness, but this always means increased tool cost and maintenance, plus the consequent delay in production caused by tool repairs. Tool cost is also increased by the necessity of providing inserts in the die (separate pieces dovetailed into the die block to prevent possibility of
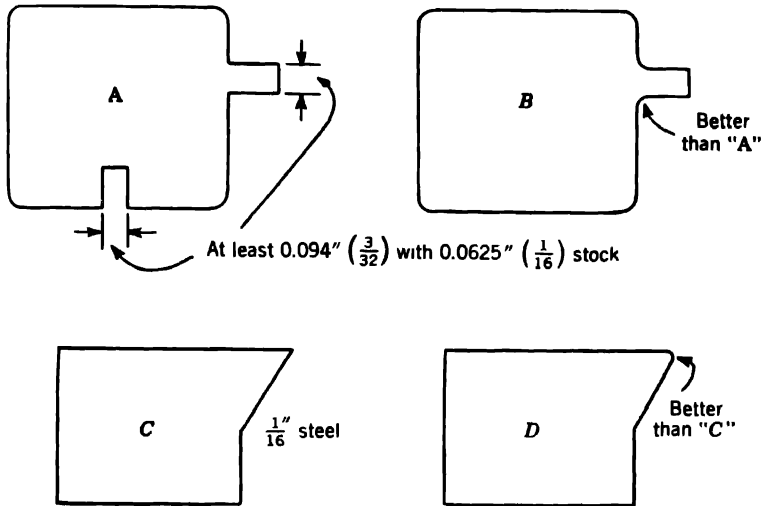
FIG. 19.11. Design of projections.

cracking in hardening), or special bushings containing groups of holes.

The distance from the edge of a hole to the edge of the nearest other hole or edge of the blank should be at least equal to the thickness of the material and greater wherever possible (see Fig. 19.12). Otherwise it is difficult to prevent distortion of the hole or edge of the blank.
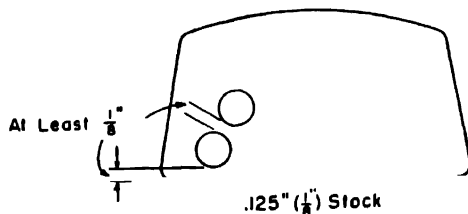
FIG. 19.12. Minimum spacing preferred between holes and edges.

Location of holes with respect to bends in the blank are important. A condition as in Fig. 19.13a, where the hole is located close to a bend, will cause distortion of the hole, as the bending action of the

material elongates the hole if pierced before bending. Such holes to be pierced before bending should be located 1½ times the material thickness plus the bend radius from the right angle member. If the hole cannot be located this far from the bend, and a round hole is

(a)

(b)
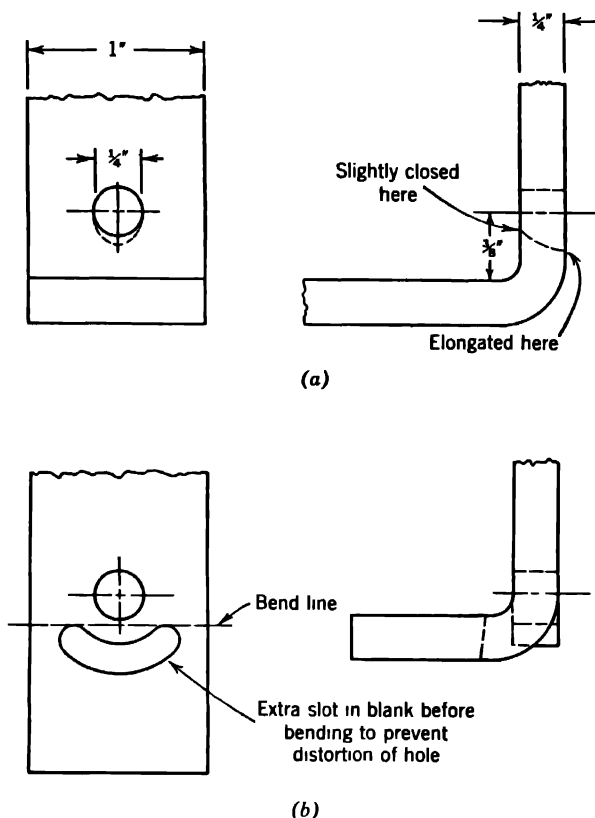
Fig. 19.13. Holes located near a bend. (a) Hole is deformed. (b) Alternative for avoiding deformed hole if requirements permit.

required, the hole should be pierced or drilled after bending. An alternative, shown in Fig. 19.13b, may sometimes be permitted for lightly loaded parts.

Close tolerance between holes should be avoided, as this increases tool cost. It may often be possible to use larger holes to insure proper location of a part in assembly, thereby increasing allowable tolerance of the center distances and diameters of holes.

The possibility of using stock dies for pierced holes should be kept

in mind, especially when making comparatively small quantities of parts. Matrix alloy dies may make possible reduced die cost, particularly for stampings with a number of pierced holes.

19.15   TOLERANCES FOR STAMPINGS

For economical tool cost, tolerances on blank dimensions should be as great as the design will permit. For instance, with the blank shown in Fig. 19.14, a tolerance of $+0.010$ in. on A, B, and C would mean

$\frac{1}{16}''$ steel
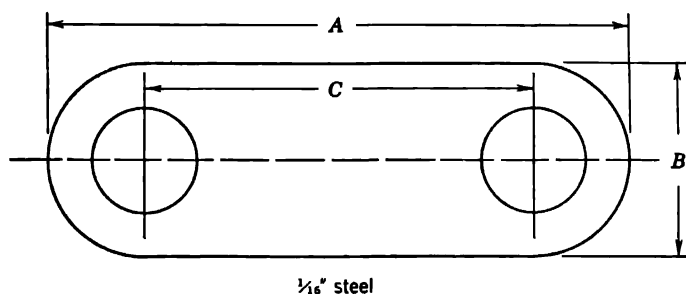
Con- dition	1	2	3
A	$4''^{+.010''}$	$4''^{+.004''}$	$4''^{+.002''}$
B	$1''^{+.010''}$	$1''^{+.004''}$	$1''^{+.002''}$
C	$3''^{+.010''}$	$3''^{+.004''}$	$3''^{+.002''}$

Fig. 19.14.   A punching and its tolerances. See description in text.

that the tool could be used without fitting the punch and die by grinding. A tolerance of $+0.004$ in. on this stamping means that the punch and die must be ground, adding approximately 35 per cent to the factory cost of the tools. If the tolerance is $+0.002$ in. or less, it would be necessary to add a shaving operation. This will mean an additional die, adding approximately 170 per cent to the factory cost for tools. The additional operation will add 150 per cent to the original labor cost.

Sometimes smooth edges and close tolerances are necessary only on part of a blank. If so, this should be specified, since it is often possible to incorporate a shaving operation on a progressive die, thus eliminating a separate operation.

Cutting action of dies frequently causes a slight rounding of the stock edge next to the punch, a smooth edge $\frac{2}{3}$ across the stock thick-

ness, and a sheared edge for the remaining ⅓ of the stock. The sheared edge often contains burrs several thousandths of an inch high. These burrs must sometimes be removed by subsequent tumbling or similar operations. If they are not to be removed, the drawing should specify the burred edge unless the part is symmetrical and can be turned over so that the burred edge will be in the correct position for assembly.

Blanking tolerances are given on the plus side. This is done because the size of the blank die determines the size of the blank produced; and as the die is ground for resharpening, the die becomes larger, owing to clearance angle on the sides, causing the blank to increase in size. For the tolerance on pierced holes, a minus tolerance is given. The diameter of a pierced hole is determined by the diameter of the piercing punch, and since the punch wears with use, the hole will become smaller and the tolerance should be on the minus side. Of course, the hole in the die for the pierce punch also becomes larger with wear, but this only increases clearance between the punch and die and results in an increased burr. It does not increase the dimension of the pierced hole in the blank.

Generally speaking, the kind and thickness of material used; the size of the part; the dimensions and number of holes or slots, and their relation to bends, periphery, and other holes, all affect the tolerances that can be maintained in blanking, piercing, and forming.

19.16   FORMING

Form dies take a variety of shapes and are often used in combination with piercing, cutoff, and other operations. Where parts are pierced, formed, and cut off in the same die, it is often very difficult to maintain a right angle at the bend, especially in the harder materials, owing to the springback of the material. Therefore, the designer should, where possible, allow for a slight deviation from an exact 90° angle. This is especially true with heavy material, for instance 0.094 in. thick. If exactly 90° is required, it may be necessary to build a more complicated die, thus adding to the tool cost, or an operation may be added, thus increasing the labor cost.

Wherever possible, forming should be done at right angles, or nearly so, to the grain of the stock (that is, to the length of the strip used). Bends made parallel, or nearly so, to the grain of the material often cause fractures on the bending line. Where bends must be made at right angles to each other in the same stamping, it is often desirable to have them occur at 45° to the grain of the stock (see Fig. 19.15).

It is often desirable to have a hole in a piece being bent to prevent creeping of the material while the piece is being formed in the die (Fig. 19.16A). However, if the pierced hole cannot be tolerated, creeping can be prevented by adding "spurs," or sharp points, in the form punch to engage the material being formed (Fig. 19.16B). This latter method will leave marks on only one side of the formed piece.

For ease of manufacture, the lengths of bent portions of a blank should have as large a tolerance as possible (Fig 19.16A). The height of short tabs and other formed portions of a blank should be

Crack occurs when bend is made parallel to grain alignment (indicated by arrows). No cracks occur when all bends are at 45 degrees to alignment
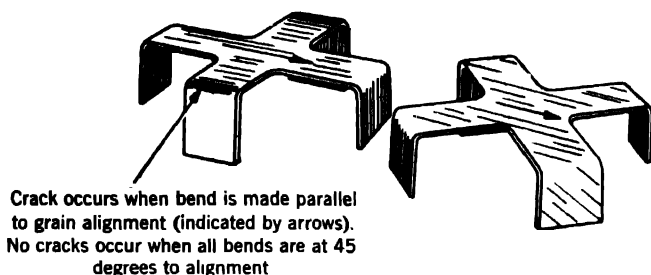
Fig. 19.15. Mutually perpendicular bends should be made at 45° to grain alignment, as at right.

at least 1½ times the material thickness plus the bend radius, since forming becomes exceedingly difficult below this dimension (Fig. 19.16C) and the tab outer edge will pull down.

Sharp radii in the thick materials should be avoided. Radii no smaller than the material thickness should be specified as a rule (Fig. 19.16D), since, with a smaller radius, the material tends to pinch between punch and die, rupturing the blank before it is drawn.

The use of spring materials where parts are to be formed (e.g., phosphor bronze, spring steel, etc.) makes it very difficult to get uniform bending. This is also true in a lesser way of the harder grades of stamping steel and brass.

The designer can often help the tool room reduce the cost of the tool and shorten delivery of it by specifying the blank development of a formed part on the drawing. It is common practice for the designer to specify the approximate development but, when this is done, it is necessary for the tool room to make first the final form die, and, by a cut-and-try method, keep experimenting with various size hand-cut blanks on this die until the dimensions of the part after forming are in accordance with the drawing. However, if the dimensions of the formed part are not too important, it is often possible for

the engineer to specify the exact development on the drawing, thus eliminating the necessity for development in the tool room. This will save time by allowing fabrication of both the blank and form dies simultaneously (Fig. 19.16D). A rule for such shapes is to consider the neutral axis of the bend ⅓ the material thickness from the inside edge.
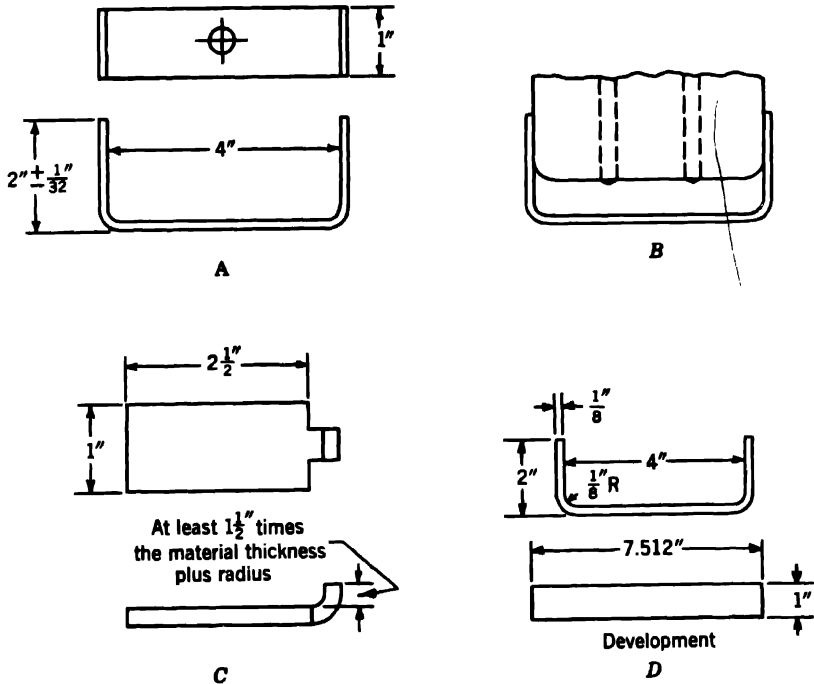
Fig. 19.16. Several designs for forming bends.

Reinforcing ribs, or stiffening ribs, properly applied to formed parts, can increase rigidity of the part 1 or 2 times. They are usually limited in height to twice the thickness of the material, and the inner radius should be equal or larger than the stock thickness (see Fig. 19.17C). To avoid distortion of pierced holes or the blank contour, ribbing should be as remote as feasible from these features. Fig. 19.17 illustrates two typical uses for ribbing to strengthen a bend (a) and to reduce warping of a flat surface (b). Joined ribs, or corrugations, in flat sections can be used for even greater stiffening .

Extruded or swedged holes are frequently called for on formed parts to provide greater thread engagement for screws than is available in
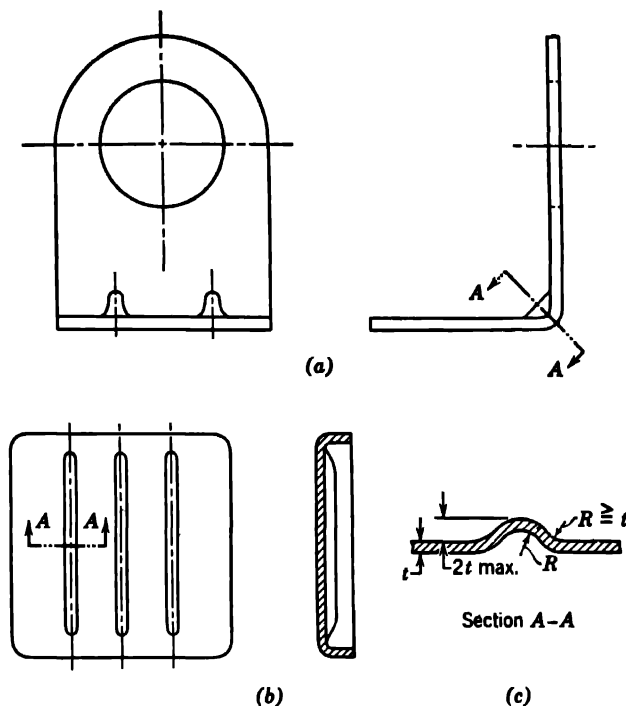
FIG. 19.17. Two applications for ribbing. (a) Strengthening a bend. (b) Improving flatness, stiffness, and strength of sheet. (c) Detail of rib.

the material thickness. Other uses are for bushings, as soldering flanges, for countersinks, for rivets or screwheads, to lighten sections and retain stiffness, and to serve as guides in telescoping parts. Ordinarily the height, H, of the swedged section (see Fig. 19.18), cannot exceed one-fifth the body size of the tap to be used, and this height can be attained only in half-hard or softer material. A good rule is to design for flange height and root-radius section material equal to the material in a circle of size B.
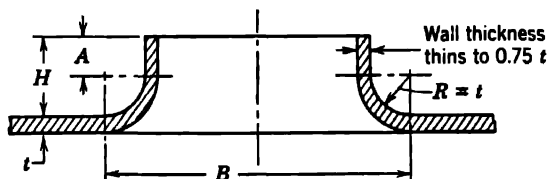
FIG. 19.18. Swedged hole. H equals total height of circular flange; A equals height of straight portion.

Location of bends with respect to blank profiles may result in a small amount of tearing or fracturing of the material at the junction. This may prove troublesome if the part is subjected to vibration or
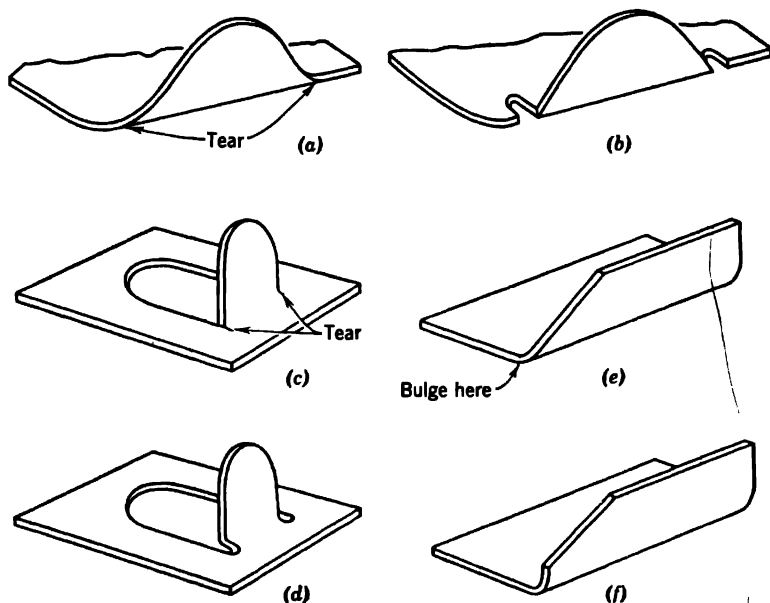
FIG. 19.19. Designs for avoiding tears: (b) shows use of a notch to avoid tear in flange junction of (a); (d) similarly shows notch to avoid tear in tab junction of (c); (f) shows relocation of flange junction to avoid bulging of (e).

fatigue loading. A common method of correction is use of relief notches at the junctions. These notches should be at least two times the material thickness in width where possible. Fig. 19.19 (b and d) illustrate two applications. Fig. 19.19f illustrates a design change which avoids placing the bend at the contour junction.

19.17 SHELL DRAWING DESIGN

In designing shells for production on a punch press, the following general comments may assist in obtaining lowest tool and manufacturing cost consistent with design requirements.

Round Shells. Round shells always involve less tool cost and generally less manufacturing cost than shells of a rectangular or irregular shape. Drawing punches, dies, and other parts for producing round shells can be turned on a lathe and ground on a cylindrical or universal grinder much quicker than the machining of irregular-shaped

dies, which must be worked out on the comparatively slower Keller machines, shapers, etc. Hand grinding and stoning for punch and die clearance are also eliminated on cylindrical forms. Manufacturing cost is often greater for rectangular shells, on account of the comparatively small radii in corners, which necessitate extra operations to draw successfully.

Flanges on Shells. Shells with flanges generally involve higher manufacturing cost and tool maintenance than shells without flanges. The latter are pushed straight through the die by the punch, whereas shells with flanges must be drawn in and pushed back out of the die. This slows up the drawing operation, and generally causes increased handling. To return the shell to the top of the die, a pad is necessary. This pad is actuated by springs or by a mechanical knockout, pushing shells out of the die on the return stroke of the draw punch. Shells with flanges, in being pushed back through the die, create considerably more die maintenance by causing almost twice the wear on the die. Also, to prevent score marks on the sides of shells, flanged-shell dies must be polished more frequently.

There are occasions where a flange is to be desired, for instance in rectangular or irregularly drawn shapes (Fig. 19.20*a*). The trimming
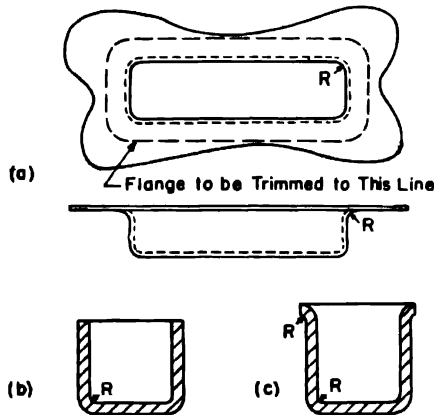
FIG. 19.20. Trimming of drawn shells.

of this shell involves a trim die similar to a blank die, whereas if no flange were shown, as in Fig. 19.20*b*, it would be necessary to trim to height (involving considerable tool cost), or draw with a flange, trim, then redraw to remove the flange, which increases manufacturing cost. Sometimes, when no flange is desired, it is possible to draw a part with a flange, then trim very close to the side, producing an

edge, as shown in Fig. 19.20c. This condition should be shown on the drawing, if permissible. Also, if the sides of a drawn part are not too high (say $\frac{1}{10}$ of the shell diameter), it may be possible to develop a blank which will draw near enough to desired height to eliminate trim. With this type, the tool department should be consulted to determine what variations in height may be expected.

Height of Shells. In drawing round shells, the maximum height that can be drawn in one operation is governed mainly by the diameter of the shell, the kind and thickness of material used, and the radius in the bottom of the shell and under the flange (if there is one). Too great a variation in material thickness will cause a variation in height of drawn shells and will sometimes cause excessive breakage. Thus, it is often advisable to use strip material for shell drawing, since the greatest thickness variations are found in sheet stock.

In drawing steel, a reduction of 50 per cent from the blank diameter can generally be obtained if the material is of deep drawing quality. This figure is calculated as the difference between the blank and cup diameters divided by the blank diameter.

To figure the approximate blank diameter of a given round shell without flange, the formula is

$$B = \sqrt{D^2 + 4DH}$$

where B is blank diameter, D is diameter of shell, and H is shell height.

In order to obtain the percentage reduction shown in Fig. 19.21, it is often necessary to anneal or copper plate when using certain materials. When drawing the stronger steels, stainless steel, brass, and copper, annealing is often used to overcome the work hardening caused by drawing operations. Copper plating is also being used extensively on steel shells before redrawing. The film of copper reduces die wear considerably and seems to act as a lubricant to prevent score marks and facilitate the drawing action. Various lubricants are also used.

Where shells are to be drawn at, or anywhere near, the maximum permissible reduction percentages, radii in the bottom and under the flange (R, Fig. 19.20) should be as large as possible. It is rather difficult to confine this to a rule, but in medium-thick material ($\frac{1}{16}$ to $\frac{1}{8}$ in.) the radius should be at least 6 times the thickness of material. For thinner materials this proportion should be increased and for heavier it may be reduced. Shells with too small radii gen-

Graphical method of determining blank dia of cup

$$H + \frac{D}{2}$$

Formula:—

$$B = \sqrt{D^2 + 4DH}$$

Blank dia = B
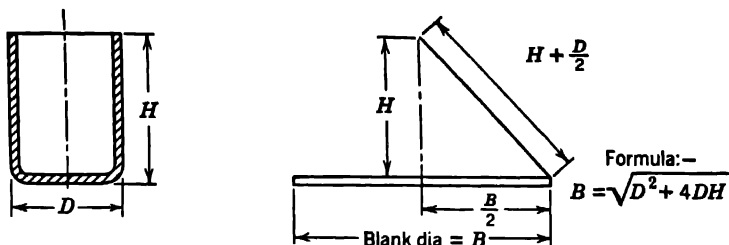
Dimensions of first draw

$$C = \frac{\text{Dia of blank}}{2}$$

$$E = \tfrac{3}{4}\,C$$
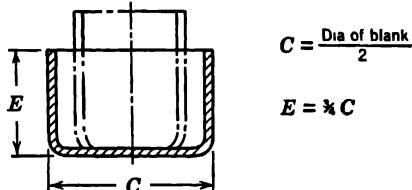
Percentage reduction of dia C

Based on thickness and material
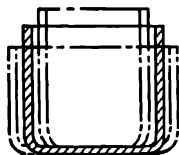
Thickness	Alum & steel	Brass
$\frac{1}{16}$	20%	30%
$\frac{1}{8}$	15%	24%
$\frac{3}{16}$	12%	18%
$\frac{1}{4}$	10%	15%
$\frac{5}{16}$	8%	12%

FIG. 19.21.   Shell deep-drawing design data.

erally require extra operations involving extra tool and manufacturing cost.   Radii in corners of rectangular shells (Fig. 19.20) should be as large as possible for the same reason.

19.18   RECOMMENDED SHELL TOLERANCES

Table 19.3 lists recommended tolerances for round shells of various materials.   With rectangular or irregular shells, tolerances should be approximately 20 per cent greater than in Table 19.3.

All the drawing tolerances listed are based on the first draw from a shell, the height of whose sides is from $\frac{1}{2}$ to $\frac{3}{4}$ the diameter of the shell.   If the sides are lower, it is possible to hold the shell to closer

Table 19.3   Recommended Shell Tolerances

Round Shells—Steel, Brass, Copper, Aluminum, Zinc

Thickness of Material	*Up to 2 In. Diam*	*Up to 6 In. Diam*
Up to $\frac{1}{32}$ in.	±0.005 in. (inside diam)	±0.008 in. (inside diam)
$\frac{1}{16}$	±0.006	±0.010
$\frac{3}{32}$	±0.008	±0.012
$\frac{1}{8}$	±0.010	±0.015
$\frac{1}{4}$	±0.015	±0.020

limits. Of course, closer limits can also be maintained by "redrawing" or "sizing." This, however, entails increased tool and labor cost.

19.19 MATERIAL FOR STAMPINGS

There are three general material factors involved in designing stampings, other than the choice of material for operating functions such as strength, wear, and corrosion resistance. These factors are use of commercial stock dimensions, hardness and formability of commercial stock, and design for high material utilization.

Commercial Stock Dimensions. Except for special springs or highly critical components that justify ordering a special mill run of raw material, the stock should be selected from forms commercially available. Wire, bar, sheet, strip, and rolled forms are produced in popular size classifications and tolerances. Since data on the latter may vary to some extent with the mill and the base metal, suppliers' handbooks should be utilized in establishing specifications. The more important gage systems for identifying dimensions of wire, sheet, and strip are given in Table 19.4.

Ferrous Metals. Low-carbon steel is employed for the largest range of stampings because it is lowest in cost and provides parts with good welding properties and good strength. For deep drawing, material having a low elastic limit compared to its ultimate strength is desired. Open-hearth steel having 0.05 to 0.08 carbon and 0.25 to 0.50 manganese is chosen for the deepest draws. The trend in large production is to purchase extra deep drawing stock on its performance in the die. That is, action in the dies is considered the test specification, and the steel practice to produce the necessary material is left to the mill (see Chapter 4).

C1010 is specified for lighter draws and the general run of stampings which do not require spring hardness or resistance to sliding wear. Material up to 24 in. wide is termed strip. Wider forms

Table 19.4   Gage Equivalents in Decimal Parts of an Inch *

Gage Number	Birmingham or Stubbs Wire Gage	United States Standard Gage	American or Brown & Sharpe Wire Gage	British Imperial or English Legal Standard Wire Gage	U. S. Steel Wire (Washburn & Moen)
0000	0.454	0.4062	0.460	0.400	0 393
000	0.425	0.3750	0.410	0.372	0.362
00	0.380	0.3437	0.365	0.348	0.331
0	0.340	0.3125	0.325	0.324	0 307
1	0.300	0.2812	0.289	0 300	0.283
2	0.284	0.2656	0.258	0.276	0.263
3	0.259	0.2500	0.229	0.252	0.244
4	0.238	0.2344	0.204	0.232	0.225
5	0.220	0.2187	0.182	0 212	0.207
6	0.203	0.2031	0 162	0.192	0.192
7	0.180	0.1875	0.144	0.176	0.177
8	0.165	0.1719	0.128	0.160	0.162
9	0.148	0.1562	0.114	0.144	0.148
10	0.134	0.1406	0.102	0 128	0.135
11	0.120	0.1250	0.091	0 116	0.120
12	0.109	0.1094	0.081	0.104	0.105
13	0.095	0.0937	0.072	0.092	0.092
14	0.083	0.0781	0.064	0.080	0.080
15	0.072	0.0703	0.057	0 072	0 072
16	0.065	0 0625	0.051	0.064	0.063
17	0.058	0 0562	0 045	0.056	0.054
18	0 049	0.0500	0.040	0.048	0.047
19	0.042	0.0437	0.036	0 040	0.041
20	0.035	0.0375	0.032	0.036	0.035
21	0 032	0.0344	0.028	0.032	0.032
22	0.028	0.0312	0.025	0.028	0.028
23	0 025	0 0281	0.023	0.024	0 025
24	0.022	0.0250	0.020	0 022	0 023
25	0.020	0.0219	0.018	0.020	0.020
26	0.018	0.0187	0.016	0.018	0.018
27	0.016	0.0172	0.014	0.0164	0.017
28	0 014	0.0156	0.0125	0.0148	0.016
29	0.013	0.0141	0.011	0.0136	0.015
30	0.012	0.0125	0.010	0.0124	0.014
31	0.010	0.0109	0.009	0.0116	0.0135
32	0 009	0.0102	0.008	0.0108	0.013
33	0.008	0.0093	0.007	0.0100	0.011
34	0.007	0.0085	0.006	0.0092	0.010
35	0.005	0.0078	0.005	0 0084	0.0095
36	0.004	0.0070	0.005	0.0076	0.009

* The trend in United States practice is to specify all sheet, strip, and wire thicknesses in decimal fractions of an inch. rather than in gage numbers.

The Birmingham wire (or Stubbs iron-wire) gage is in very limited use in the United States. The United States standard gage is utilized for most commercial iron and steel strip, sheet, and plate. This gage was originally established by Congress in 1893 as a weight gage based on iron at 480 lb/cu ft, and the numbers apply to even ounces weight for a 1 sq ft section. The manufacturers' standard for sheet steel adopted by the A.I.S.I. is 4 per cent thinner, since it is based on density of steel. The United States steel wire gage (also known as Washburn & Moen gage, American Steel Wire Co. gage, steel-wire gage, and, with certain sizes rounded off to even thousandths, the Roebling gage) is used for steel wire. The Brown & Sharpe wire gage (also known as American Wire gage) is used for almost all copper and aluminum wire, especially in the electrical industry (see Chapter 6) and for all nonferrous sheet and strip.

The British standard wire gage (also known as New British Standard, English legal standard, and Imperial wire gage) is a modification of the Birmingham wire gage and is used for manufacture of British ferrous and nonferrous wire and nonferrous sheet. Other gages are sometimes used for music wire, drill rod, twist drills, and sine sheet.

are termed sheet. As-sheared or specially rolled edges can be specified for strip, the latter being specified only when their extra cost is justified in the product. Hot-rolled strips, 23 to 7 gage, of this class are given a high-temperature cold-reduction pass of ½ to 1 per cent to work the material approximately to its yield point and thus eliminate stretcher strains (waviness) in flat stampings. The hot-rolled variety may have some surface roughness and scale and therefore is not used when surface finish is important. Cold-rolled sheet and strip (30 to 7 gage) is reduced 35 to 50 per cent approximately to the final gage, pickled, and then given a sizing pass of ½ to 1 per cent reduction to the final dimensions. Tempers of cold-rolled strip available are dead soft (No. 5), skin rolled (No. 4), planished ¼ hard (No. 3), ½ hard (No. 2) and full hard (No. 1). The degree to which the harder tempers can be formed without cracking depends on the radius and the stock thickness, but in general the ½ hard will bend 90° with or across grain about an almost sharp radius. Hard temper is generally limited to 45° bend under the same conditions and ¼ hard will bend back on itself across the grain and 150° with it. The harder varieties have greater spring back in forming and require closer die clearances.

In higher-carbon steels, an additional spring temper is available for spring uses. The formability of these grades is less than for the low-carbon type, but is suitable for many types of blued-steel flat springs for latches, etc.

Stainless steel is often used for stampings to take advantage of its corrosion resistance. It is more costly and more difficult to form, but parts with as much deformation as for low-carbon steel are made by slower-acting, more-rugged presses. Dies require 1½ to 2 times the clearance for stainless steel, and bent parts have 2 or 3 times the spring-back. Soft-temper stainless is used for deep drawing, and annealing is used between draws for the highly deformed shapes.

Aluminum. Tempers available in aluminum are 0, ¼, ½, ¾, and full hard. Larger radii are required for bending and drawing than for steel, and the radius required varies with the grade alloy and the stock thickness. Better die finish is also required.

Magnesium. Magnesium sheets can be given limited cold forming if the die action is slow and die clearances large. Sharp bends and deep draws must be performed at 500 to 700 F.

Copper and Its Alloys. The bronzes, brasses, and commercially pure copper are furnished in ¼, ½, ¾, and full hard and in extra-hard, spring-hard, and extra-spring-hard tempers. Light-drawn ma-

terial, softer than ¼ hard, is used for shallow drawing, but soft-annealed sheets are needed for deep drawing and best surface. Bend radii for ¼ to full hard tempers are approximately the same as for steel. The extra-hard temper can be formed about a sharp radius 60° across the grain and 45° with the grain. Spring brass can be given bends similar to extra-hard temper, but in usual applications the thickness of stock and the radius of bending alter the amount of forming that may be done.
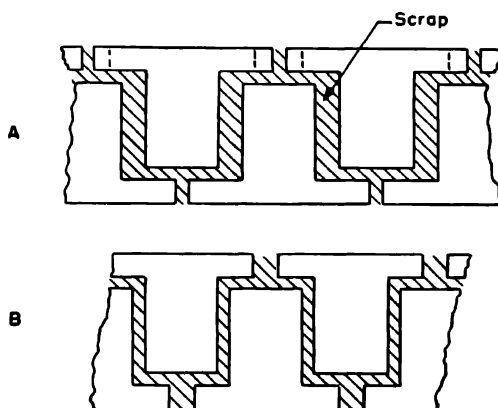
FIG. 19.22. Design for material saving. Note reduction in scrap in *B* versus *A* obtained by shortening projecting ends to dotted lines in *A*.

For piercing and blanking operations, most grades of material will punch satisfactorily, except that scaly material tends to shorten die life and to increase die-grinding costs when a large quantity of stampings is to be produced.

Where forming operations are involved, it is often desirable to use a strip material, since greater thickness variations are experienced in sheet material, and these variations will destroy the uniformity of the bending angle. Forming dies must usually be tried with the material and the lubricant to be used as they influence the action. Some relieving and polishing of the dies are usually required for proper action.

Material for stampings involving swedged portions should be ductile. It is often necessary to "spot anneal" (anneal a small portion of the blank adjacent to the hole) to swedge to the required height without cracking. An annealing operation may also be needed on the corners of a drawn shell to avoid cracking during subsequent trim operations.

FIG. 19.23. Several examples of nesting for material saving. Percentage figures indicate scrap saved by respective arrangement over adjacent alternate.
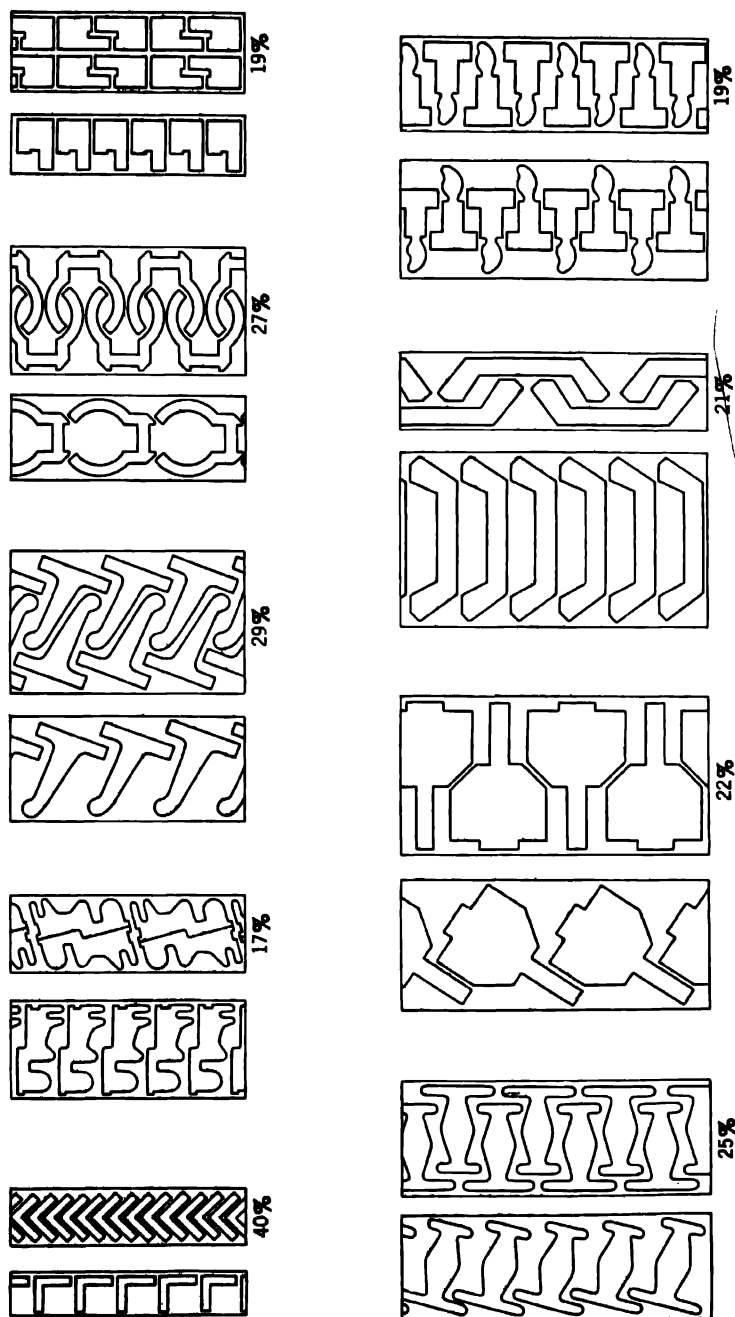
Where large quantities of parts are required, they are processed in automatic presses with roll feed. Here it is generally desirable to have strip stock in coils to reduce operating labor. This applies to all materials 0.044 in. thick and under. In some press shops, roll straighteners are available to straighten material before it is run through the feed rolls to the press. In this case, material even heavier than 0.044 in. is purchased in coils.

Material utilization should be studied carefully when punched parts are designed. Often, slight changes can be made in design of parts that will considerably lessen the quantity of material used. For example, consider the stamping indicated in *A*, Fig. 19.22. Here, there is a considerable waste of material. If the projecting *T* ends are shortened as in *B*, Fig. 19.22, there is very little scrap material between blanks. Many other examples may be found where slight changes in blank shape or size will reduce the material used (see Fig. 19.23). It is, of course, no help to widen the blank simply to utilize the material.
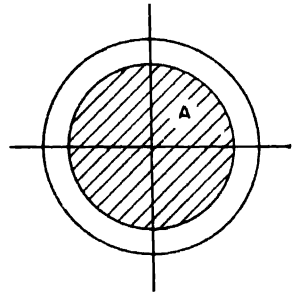
FIG. 19.24. Scrap centers, *A*, should be considered for other parts.

Whenever rings or circular pieces are required (Fig. 19.24) or any stamping involving the piercing of a comparatively large center, the apparatus should be studied to see if some other part cannot be designed in such a manner that the scrap center (*A*) can be used in producing it.

19.20 STAMPING COST

The type of die selected for a given stamping should, in general, be the die that will produce it at the lowest total cost. In selecting a die the following factors should be considered.

(*a*) Total quantity of stampings to be produced.

(*b*) Rate of production required.

(*c*) Direct labor cost per 1000 stampings.

(*d*) Material punched.

(*e*) Cost of dies.

(*f*) Cost of maintaining dies.

(*g*) Cost of setting up dies.

(*h*) Time required to produce dies.

(*i*) Expected life of dies.

(*j*) Flatness and accuracy of stamping.

As an example, assume that a product order requires 200,000 discs of ¾-in. diam. They are to be made of ¹⁄₁₆-in. common sheet steel. Consider two methods of making these stampings: (1) using stock dies, and (2) using a 5-gang die.

In order to effect material economy these discs must be punched as shown in Fig. 19.25.
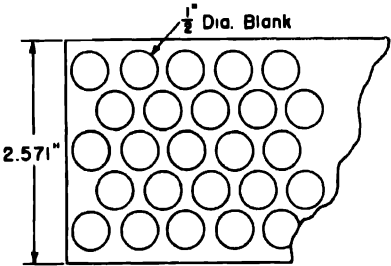
FIG. 19.25. Nesting of discs for material saving.

In the first method a single punch and die is used, but the operator stagger punches the material to obtain economy, as shown in Fig. 19.25. This is done by locating material over the die by eye, and although there will be slightly more material used with this method than with a 5-gang die as in the second method, where the least possible spacing between blanks is built into the die, for the purpose of this comparison the material utilization is considered equal for both methods.

The following data may be used in selecting the type of die most economical for the above conditions. (No future use for the die is contemplated after the present order is completed.)

Costs	Stock Die: Method 1	5-Gang: Method 2
Die cost		
Labor		$40
Material		2
Total		$42
Operating cost		
Labor per thousand stampings	$ 0.335	$ 0.0235
Total	67.00	4.70
Cost of setting up tools	0.29	0.64
Maintenance (including grinding and resetting), 3 grinds	0.60	
Total cost	$67.89	$47.34

The low operating cost shown in method 2 is possible because this die can be run in an automatic press at a speed of approximately 150 strokes per min, producing 5 discs per stroke or 750

per min, whereas method 1 requires the use of a die in a hand-operated press, producing one blank at a time.

From the figures below it is apparent that with the quantity indicated, a gang die should be made. Had the quantity been 100,000 or less, it would have been more economical to use the stock-die method.

Other Cold-Working Processes

19.21 STRAIGHTENING

These operations are usually auxiliary to the other processes. Press straightening of heavy sections is performed both for stock and for finished pieces. Contour roll and angular roll straightening are used for tubes and bars, the latter being suited to all contours. Roll straightening with multiple cylindrical rolls is also used for sheet and strip, both at the mill and also as an operation in feeding material, particularly roll stock, to presses.

Another method of straightening used for wire, bar, and sheet is stretcher straightening. For sheet it is often called stretcher leveling. In this operation, grips on each end of the stock apply tensile forces just beyond the elastic limit of the material and by local yielding cause the form to straighten taut between the grips.

An application of the stretch method of forming is made in the tangent bender where stock under tension is bent about and tangent to formed die plates or bars. A typical application of this process is to outer liners or cases for refrigerator cabinets, both sides and the top with flanges being made in one bending operation from notched stock.

19.22 SPINNING

Metal spinning is a technique for forming round sheet-metal parts at low cost. Complex cylindrical shapes can be spun in aluminum, copper, pewter, zinc, brass, low-carbon steel, and certain of the alloy steels, including stainless steel.

The machine used for making spun parts is a lathe that is larger, more powerful, and normally has a greater swing than the familiar wood-turning lathe. A form that has the same shape as the spinning to be produced is first turned on the lathe from either wood or metal. For large work, wood is usually preferred because it costs much less. This form serves the same purpose in spinning

that a die serves in forming. It is much lower in cost than the corresponding die, but can be used over and over again for making duplicate parts. The form may also be made so that it can be dismantled for removal from the finished spinning. Partially closed ends and reduced sections may thus be spun that would be practically impossible to draw.

The form is usually fastened directly or through a backing plate to the headplate of the spinning lathe, and the round sheet-metal blank, which is to be spun, is pressed against the form by the tailstock. When the lathe is started, both the blank and form are rotated at high speed. The operator, beginning at the center, works the metal against the form with blunt-ended hard wood or steel rods. A skilled operator can fit the metal to a small and simple form in just a few minutes. Intricate articles may require several operations with intermediate annealing before they are spun to the finished shape.

The skill of the operator plays a very important part in successful spinning, not only in limiting work hardening, but in using the proper tools with the proper pressures to form the desired shapes. The tools and technique of spinning are considered "stock in trade." Tolerances on dimensions produced by skilled spinners are $\pm \frac{1}{64}$ to $\pm \frac{1}{32}$ up to 24 in., $\pm \frac{1}{32}$ to $\pm \frac{1}{16}$ from 24 to 48 in., and $\pm \frac{1}{16}$ to $\pm \frac{1}{8}$ for 48 in. and larger.

Spinning is not a new process. It has, in fact, been used for years to make trophies, loving cups, cooking utensils, chandeliers, lamps, reflectors, urns, and similar articles. In industry, this method of forming parts has been found particularly applicable for small orders of, say, up to 20 duplicate pieces. It is used for model work in conjunction with development and research, and for parts for the specially engineered industrial or apparatus lines. The small parts may be held to good accuracies, and all the parts have characteristic light weight, smooth surfaces, and good strength, which is introduced by cold working.

As with most other special processes, the designer can often save time and improve his product if he will consult the experienced operator in the early stages of design. Simple changes in shape may often eliminate an annealing operation, or make the wood form much simpler, and attendant savings result. Usually it will be found that the various forming and shell-drawing operations are less expensive than spinning, if the quantity desired is large.

Any metal with moderate ductility can be formed by spinning. Thicknesses are limited by the strength and work hardening of the material and by the forces that can be exerted by the spinner. Typical limits to thickness are for aluminum, brass, bronze, and copper, $\frac{1}{4}$ in.; low-carbon steel, $\frac{3}{16}$ in.; and stainless steel, $\frac{1}{8}$ in. It should be recognized that material thickness in the finished part will depend on the work necessary in forming. Some sections will be reduced in thickness where the material is drawn out; others will be thickened by gathering.

19.23 COLD ROLL FORMING

Roll forming consists of passing strip stock between sets of shaped driven rollers. The sets of mating rollers progressively form the strip to the desired shape. The process is made continuous by the use of guides between sets of rollers.

Most of the ductile strip and sheet metals may be successfully roll formed. Metals from 0.005 to $\frac{3}{4}$ in. thick have been formed by this method. The process is particularly applicable for producing large quantities of long lengths with a minimum of handling.

The two types of machines in general use are the double-housing type and the overhung type. The double-housing type has bearings on either side of the rollers and is capable of taking much heavier work than the overhung type, which has both bearings on one side of the roller.

19.24 SHEARING

Metal shearing machines are made in a variety of ways, but there are four major classifications.

(1) Open-front shears have one fixed and one movable blade. The movable blade may be hinged, as in the ordinary household shears, or may be guided, as in a punch press.

(2) Closed, double-housing shears are somewhat similar to a power-press brake. The blades are long and guided in the housing at each end.

(3) Rotary slitting shears have a series of cutting rolls on upper- and lower-driven shafts. Width of rolls and spacers between rolls govern the width of strip to be cut, and allow a wide sheet to be cut into several strips in a single operation.

(4) Circle-cutting shears have an upper and a lower cutting roll. The work revolves about an adjustable center, which may be a pad, centerpoint, or arbor, and a round blank is produced.

On straight-blade shears, the upper blade is usually set at a slight angle with relation to the lower blades, so that the cutting action starts at one side and progresses across the sheet. This reduces the pressure required to complete the shearing. A hold-down is usually used to prevent movement of the sheet during the cutting.

Special shearing machines have been developed to cut off rolled shapes such as channels, angles, and beams. These may have blades shaped to fit the section being cut to prevent distortion of the piece. This requires high pressures as the entire section is sheared at once. Another method uses two blades at the bottom that are shaped to fit the section. The upper blade passes between the two lower blades and removes a strip of metal. The upper blade is made to a shape different from that of the work piece, so that the cutting is progressive and the pressure is reduced.

Another cutoff shearing operation is performed by the so-called flying shears used on continuous process machines such as rolling mills, cold roll forming machines, etc. The mechanism is so timed that, during the shearing action, the shears travel with the continuously moving strip. After the separation of the strip is completed, the shears move back to the starting point for the next cycle.

19.25 ROTARY SWAGING

Machines for this work are limited to reducing wire, bar, or tube for such parts as torque tubes, steering posts, drag links, and exhaust pipes for automobiles and to pointing and stepping seamless tubing for fishing rods, golf-club shafts, etc.

Working is performed by rotating dies that strike the work numerous rapid blows under the actuation of a pair of backing rolls. The work is elongated as its diameter is reduced. Parts usually worked in this manner have nearly circular sections, but flat-sided ovals, hex, and square sections and tapered lengths can be produced by proper die and backer-roll design. The operation may be performed hot or cold, depending on the metal and the amount of reduction required.

19.26 COLD HEADING

Cold heading is a cold upsetting process used to produce a great variety of small machine parts from wire stock. It is so named because it was originally used only for the production of heads on rivets and screws. Today its field of application is considerably wider.

A cold-heading machine is much like a forging machine in principle and operation, except that it takes wire in reel form, cuts off

the required lengths, and carries them through the upsetting operations automatically. Once set up, a heading machine can turn out 150 to 300 pieces a minute, and requires no attention other than a periodic inspection. This feature accounts for the remarkably low cost of cold-headed products.

The principal limitation of this process is the size of the parts that can be made, since the power requirements for a given size are much greater than for hot upsetting. Wire up to ⅝ in. diam is commonly handled by this process. The severity of upset possible without splitting the metal or buckling it is also somewhat less than in hot forging (see Chapter 18).

19.27   COLD-HEADING TOOLS AND THEIR ACTION

Fig. 19.26 shows the setup for producing a simple rivet. The straightened wire stock, A, is fed through the cutoff die, B, until the proper amount protrudes. The shear, C, then moves in, severing the protruding portion and carrying it over to the upsetting die, D. The punch, F, moving forward, shoves the blank into the die, D, until it strikes the stop pin, E. The continued travel of the punch upsets the protruding end of the blank, forcing the metal to assume the shape of the punch cavity. As the punch recedes, the stop pin, E, moves to eject the finished rivet from the die.

When a length no more than 2½ wire diam must be upset, a single operation is usually sufficient. When more material than this is required (up to a maximum of about 5 diam), a double-stroke operation must be employed. In this event, two punches act in succession on the blank while it is in the upsetting die, the first, or coning punch (Fig. 19.27b), gathers the stock into a stable, nonbuckling cone, the second, or finishing punch (Fig. 19.27c), produces the desired shape.

Fig. 19.26.   Schematic illustration of cold heading. See text.

In either single- or double-stroke heading, a part of the shape may be machined into the die as well as the punch. Indeed, for flat-headed screws, the entire finishing impression is in the die.

For parts where over 9 diam of the stock are in the die, the upsetting of the portion within the die makes it stick so tightly that the ejector pin may not be able to remove it. Therefore, an open die is

(a)   (b)   (c)
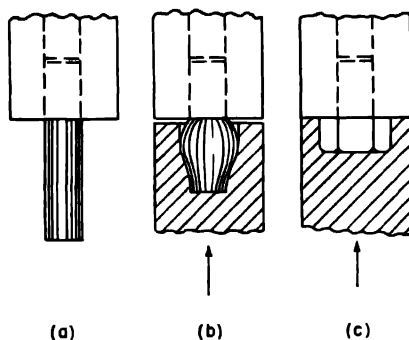
Fig. 19.27. Double stroke heading. (a) Original stock in position for heading. (b) First stroke in heading, gathering to an intermediate form. (c) Second stroke heading to a final form.

used. The stock is made to come in through grip dies as in the forging machine. After heading, as with a solid die, the dies separate, and the part, severed in the meantime from the stock, drops out.

By making a hole equal to the wire diameter and of the proper depth in the punch, an upset may be produced in the middle of a piece, as shown in Fig. 19.28. Ejector pins, P, must be provided in both the punch and the die. Double-stroke upsets are possible with
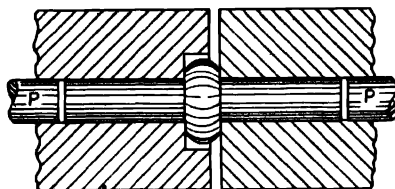
Fig. 19.28 Headed upset not on end.

this class of work but are difficult because there must be two ejections from the punch.

When a screw is to be roll threaded (see Sec. 19.30), it is often desirable to reduce the diameter of the threaded portion so that the threads will not extend above the body of the screw in the finished product. To produce this reduction, the thread end of the die is made to the required smaller diameter and the stock is forced into

it by the punch (Fig. 19.29). When the extruded portion strikes the ejector pin, *P*, the upsetting of the head proceeds in the usual manner. Any metal that is reasonably malleable and does not work harden
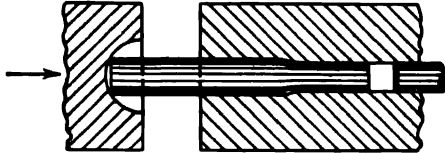
Fig. 19.29. Extrusion of thread section during heading.

excessively can be cold forged in a header. This includes low-carbon steels, low-alloy steels, structural stainless steel, and almost all non-ferrous alloys.

19.28 RIVETING

Riveting is an assembly method for fastening metal parts or metal and nonmetal parts together. The rivets used are previously provided with a head of particular form. After insertion, the shank end is formed with a die set or forming tool by hand or by mechanical, hydraulic, or pneumatic machines or hammers, depending on the size. Shank spinning is also used for tight riveting of small parts.

The rivet-head shapes selected depend on the fastening requirements. Heads of greatest stiffness and strength are used for tensile loads; wide flanges for soft material; and countersunk to improve clearance and appearance. Large rivets (above $\frac{1}{2}$ in. diam) are manufactured according to the standard ASA-B18.4-1937, and are used for structural work such as bridges, buildings, and ships, according to specifications and codes applying to the particular product. Boiler rivets have somewhat different shapes and are standardized both as to shape and application in the ASME Boiler Code, which applies to pressure vessels in general. Small rivets ($\frac{7}{16}$ in. diam and under) are standardized according to ASA-B18a-1927. The smaller sizes are often furnished with tubular shanks for ease in application when large holding forces are not required. Coopers rivets are a special type having a stubby conical head and a small cylindrical flat. Similar rivets are used for belting applications, often with a split shank for cleating. In general, a length of material equal to the diameter and not above $1\frac{1}{2}D$ is allowed for riveting in the smaller sizes. Smaller values apply to the larger sizes, particularly where the tubular rivet is to be flanged over.

19.29 HUBBING

This is a special die-forming process used particularly for simple plastic molding dies. The contour of the part is first worked out on a master hardened punch. This is then pressed at slow rate into the die block under a hydraulic press until the die impression is complete. Low-carbon steel or mild low-alloy steel in the annealed state is usually used for the die stock. Good detail and considerable deformation can be obtained by this method, which may have application to finished parts also.

19.30 THREAD ROLLING

Thread rolling is a method of producing external threads by rolling the part to be threaded between hard serrated plates or cylindrical dies that form the threads by a squeezing action. This process frequently follows cold heading as a means of making a complete screw without machining.

Figure 19.30 shows diagrammatically a pair of plane roll threading dies with a screw blank between them. On the faces of the dies are long, straight projections having the profile and pitch of the desired thread and inclined to the line of travel by an angle equal to the helix angle of the screw. The two dies are set so that the distance between the roots of the die teeth equals the outside diameter of the finished screw. Then, if the blank is prepared with a diameter approximately equal to the pitch diameter of the screw, metal will be displaced from the region below the pitch circle of the screw to form the peaks of the threads beyond the pitch circle when the blank is rolled between the dies, as indicated in Fig. 19.30.

Stationary Block

Fig. 19.30. Action of roll-threading dies.

Fig. 19.31 shows the two-die and three-die cylindrical die thread rolling methods. The rotating dies are moved in against the blank

and form the thread in the same manner as plane dies. The pitch diameter of the cylindrical dies is equal to, or some multiple of, the pitch diameter of the screw being produced.

(a)

(b)
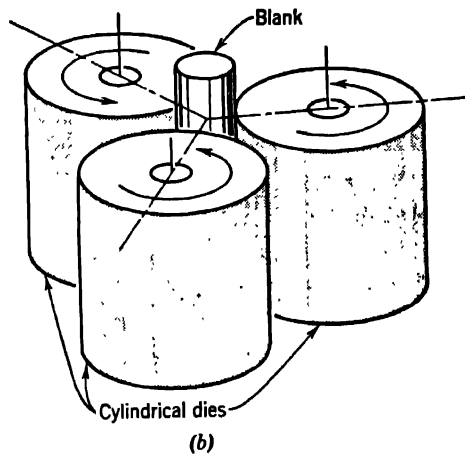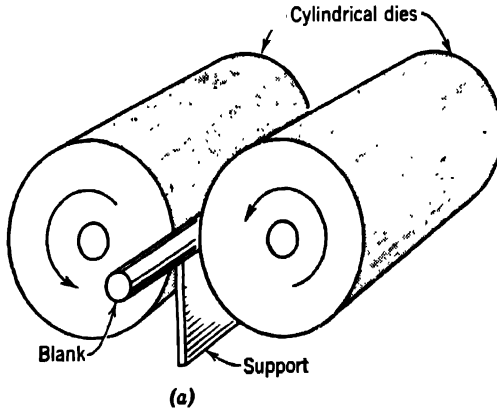
Fig. 19.31.   Cylindrical die-thread rolling.   (a) Two-roll, and (b) three-roll methods.   Rolls have tooth form and pitch circumferentially.

As in cold heading, the screw blanks are fed automatically. This makes high production at low cost possible.

Although not as accurate as the best cut screws, roll-threaded screws meet most commercial requirements (class 2 and 3 fit), and they are as much as 20 per cent stronger than cut threads.

19.31   WIRE FORMING AND STITCHING

The term "wire forms" is given to wire and ribbon products shaped in a wire-forming machine, which is considered a speciality rather than a general-purpose equipment. These machines are arranged with a roll stock feed and metal cutoff mechanism. There are multiple slides, each containing a forming die, which perform bends in sequence. If the part form is too elaborate to finish with the four slides usually provided, a second and even a third level of die-form sections may be prepared in each die for successive operation at the new positions. A great variety of wire products, similar in complexity to wire puzzles, are produced by this method.

Fence wire, expanded metal (lanced and then drawn to an expanded section), mesh, shelving, wire baskets, helical and conical springs with various types of end turns, and many other wire products come under this classification but are outside the scope of this chapter. All these products are made on specially developed machines, usually by manufacturers who specialize in the processes.

An interesting application of wire forming is the relatively new process of metal stitching. It is similar to the metal stapling of papers, but utilizes stronger equipment and heavier wire of high strength, and will penetrate metal thicknesses as large as $\frac{1}{8}$ in. It promises to find important applications in the high-production industries.

19.32   COLD-PRESSURE WELDING

This process is similar to hot-pressure welding described in Chapter 18, but the materials welded are not preheated before processing.

Welds are made by punching or rolling two or more sheets together with sufficient pressure to cause as much as 70 per cent reduction in overall thickness. It is possible that the high reductions produce temperatures from localized pressure and friction which are in the recrystallization range. But, whatever the mechanism, similar metals may be joined into joints in which the original boundary and faying surfaces are no longer identifiable.

Because of the advantages to be gained by this process, considerable development work has been done on its application to joining aluminum sheets. Very good cleaning has been necessary to production of good welds; weld length has been limited by die designs that produce the high reductions needed throughout the length of the weld; and the high deformation has resulted in greatly weakened material next to the weld which has less strength than the weld itself.

A number of development applications of the process have been reported in England and, with further work, suitable uses will undoubtedly arise in the future.

19.33 CONCLUSION

When apparatus of a limited expected production is designed, it may be advisable, at times, to use machining, spinning, casting, etc. This is especially true where design requirements are rather inflexible and are complicated by unavailability of stock tools for cold working, since the cost of stamping or heading tools may over-balance the saving on manufacturing cost. But wherever the anticipated production quantities are at all sizable (often as low as 200 or 300 pieces), the apparatus should be closely analyzed to determine the advisability of modifying the design for press or cold-work processes.

It is often possible, for low production, to avoid the use of expensive tools by making a stamping in two or more pieces, which may be welded together by arc, atomic, line or tack welding, or spot welding. Many times it will be found that the component parts may be processed on existing stock dies, thus eliminating tool expense.

As the anticipated production increases, so does the need for simplification of design. With a production of only a few hundred pieces, the total manufacturing cost of all parts to be produced may not be great enough to be affected materially by the elimination of an operation. However, where hundreds of thousands of parts are involved, a slight change on a part to permit a reduction in the size, kind, or thickness of material, or the elimination of even one operation, will often result in prodigious savings.

Although every effort in product design, methods, and tool design should aim for minimum stamping costs, the ultimate goal of minimum over-all cost of the end product should be determining. In Fig. 19.32*a* is illustrated, for example, a component involving two pieces and a riveting operation. With only moderate production, the alternative design illustrated in Fig. 19.32*b* offered enough savings to more than offset the increased die costs and additional cold-working operations. Such reductions in the number of pieces, by combining functions and redesign of components, should be evaluated before the design is frozen and tooling started.

Often the investment in equipment available will dictate the trend in design, and it will be found that many times a discussion of the part in question, between the design engineer and the methods and tool designers, will bring about recommendations for part changes

½" × ½" × ¼" angle

3"

⅛"

A

4"

Enlarged view
at A

(a) Old design

3"

⅛"

4"

Ribs (2)
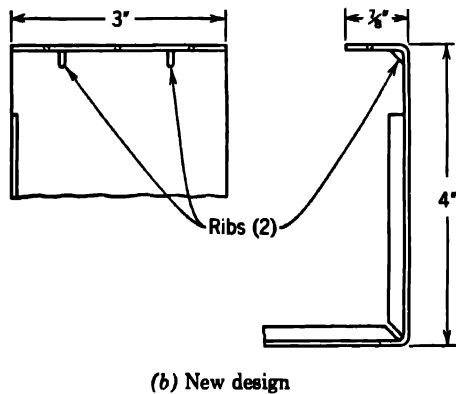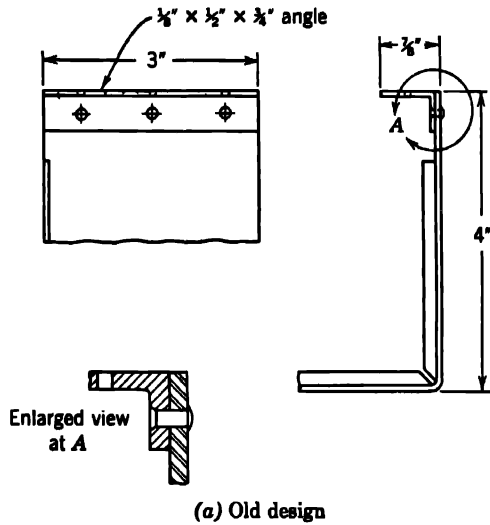
(b) New design

FIG. 19.32. Separate angle pieces and riveting operation in old design (a) are eliminated in new design (b), effecting an over-all cost reduction although die costs and cost of the single stamping were increased.

which, while retaining the limiting elements of design requirements, will greatly simplify manufacturing procedure. In other instances the choice may be to new equipment that is a justified increase in investment because of the economics in producing the anticipated quantities.

Review Questions

1. Press tools for cold-working operations contain a punch and a die. Which parts are usually designated by these terms?

2. What is meant by a single-station die? How does it differ from a progressive die?

3. Dies used for producing stampings may be divided roughly into three types. Name and describe each of them.

4. What is the main advantage of a rubber die member?

5. Describe what is meant by available die life. Name three factors related to the design of a part that affect die life. If the die section available for resharpening before the part becomes oversize is $\frac{1}{2}$ in., what is the available die life? If reground before the start of each production run of 30,000 pieces, what is the available die life?

6. When a sectionally constructed die is to be used, what type corners are preferred? when cutting off strip stock? when blanking with a solid die?

7. What general rule is normally used as a limit to the minimum size of hole that should be pierced? How close may holes be placed to an edge in normal practice? to a bend?

8. Should the tolerance on blanked parts be given on the plus side, the minus side, or split both ways? How should the tolerance on a pierced hole be specified?

9. What is the preferred orientation of stock grain to bends in forming?

10. Illustrate the use of ribbing, notches, and a swedged hole. What are their uses?

11. What gage system is most used for steel wire, for steel strip and sheet, for nonferrous wire, and for nonferrous sheet?

12. How does temper hardness of stock affect severity of forming operations? In general, what tempers in aluminum, low-carbon steel, stainless steel, copper, and magnesium may be bent 180° flat on itself?

13. Name five factors affecting stamping cost that should be considered by the tool designer when selecting a die.

14. Explain the metal-spinning process. What shapes can be produced? Under what circumstances is the process used most advantageously?

15. For what type of work is cold heading employed? Explain the roll-threading process. If a rolled thread must not be greater than the unthreaded stock diameter, what preparation must the shank receive before threading?

20 WELDING AND ALLIED PROCESSES

20.1 INTRODUCTION

Welding is defined as the intimate joining of metals wherein coalescence is produced by heating to suitable temperatures, with or with-
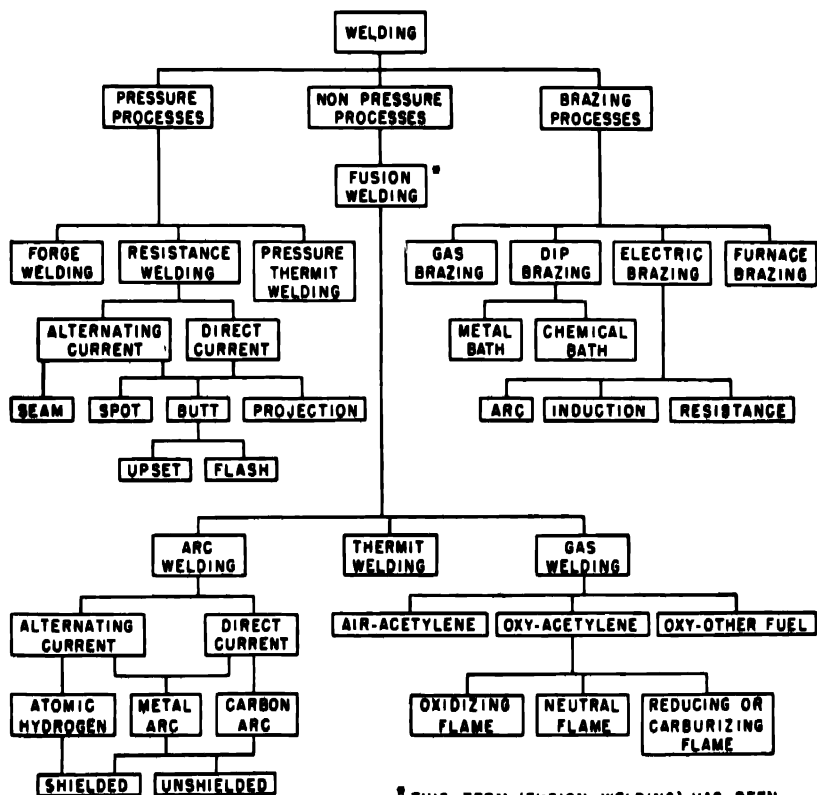
Fig. 20.1. The American Welding Society's master chart of welding processes.

out the use of either pressure or filler metal. The many methods by which welds are made are therefore classed as *pressure processes, nonpressure processes,* and *brazing processes.* In the pressure processes

parts are forged together when in the plastic state; actual melting may or may not occur. In the nonpressure processes parts are fused, or melted, together. But in the brazing processes a lower-melting-point filler metal is used to join the parts; no forging action is present and the parts do not melt.

The methods of heating commonly employed with each of these three classes of welding processes are indicated in Fig. 20.1. The various methods of brazing, resistance welding, arc welding and gas welding are of most importance to industry. Each will be discussed in this chapter, along with several allied processes closely associated with welding in purpose or in equipment used. The allied processes are soldering, flame cutting, and metallizing.

BRAZING

by R. S. PELTON *   \

20.2 THE BRAZED JOINT

The coalescence in a brazed joint is produced by heating to a suitable temperature above 800 F and by using a nonferrous filler metal having a melting point below that of the metals to be joined. The molten filler metal must wet the surfaces of the parts being joined. It must also be held and distributed in the joint by capillary attraction so as to fill the free space. A limited amount of alloying between the filler and the parts usually takes place at the elevated temperature. As a result, the strength of a brazed joint, when properly made, is somewhere between that of cast filler metal and the strength of the metals comprising the parts.

The factors upon which the strength of a brazed joint depends are:

1. The nature and strength of the metals comprising the parts.

2. The nature and strength of the filler alloy. Four types of fillers are commonly used, and the brazing processes are often classified according to the type. They are copper, copper alloys, silver alloys, and aluminum alloys.

3. The amount of alloying that occurs in the joint.

4. The clearance of the parts being joined. Except for brazing with copper in a controlled atmosphere, the filler will not enter a joint between two pieces if they are held tightly together. If the opening is too great, the resultant strength will be that of pure cast filler alloy. There seems to be an optimum spacing for each filler.

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5. The cleanliness of the materials involved. If either maximum or uniform strength is wanted, too much attention cannot be given to having the surfaces to be joined, the fillers, and the fluxes clean and fresh.

6. The use of a flux. A flux is used with most fillers to protect the cleanliness of the surfaces and to promote the flow of filler into the joint.

7. The heating and cooling of the assembly. Sometimes the brazing processes are classified according to the method of heating, as will be discussed later. The joint should not be disturbed in any way while the filler metal is cooling through its plastic range, and no load should be placed on the joint until it is cooled appreciably below the softening point of the alloy. If pressure is applied to hold the parts together while heating, the pressure should not be released until the filler metal is solid.

20.3 COPPER BRAZING

The high melting point of copper (1982 F) limits its applications as a brazing material to ferrous metals and other similarly high-melting-point alloys, including high-speed steel and tungsten carbide. Copper is most frequently used in furnace brazing at 2000 to 2100 F with a protective atmosphere, since under these conditions it is extremely liquid and often wets and flows over the surfaces very rapidly. It is practically impossible to get a joint too tight or too well fitted for copper to penetrate when a protective atmosphere is used.

Fig. 20.2. Photomicrograph of a joint between two pieces of steel of slightly different analysis copper-brazed in an electric furnace with a controlled atmosphere. Approximately ×50.

Joints in steel parts brazed with copper have high strength resulting from a combination of copper penetration along the grain boundaries of the sides of the steel joint, and the growing together of the grains so that the two surfaces are practically knitted together. This is illustrated by the photomicrograph, Fig. 20.2. The strength of copper-iron alloys that may be formed in the joint is indicated in Fig. 20.3. External fillets of copper usually are small and of little

value compared with the alloy formed in a well-fitted joint, especially if the layer of filler is thin.

Applications. Copper brazing is largely applied to assemblies made of low-carbon steel in the form of stampings, screw-machine parts, and tubing that can be heated in a furnace. However, alloy steel,
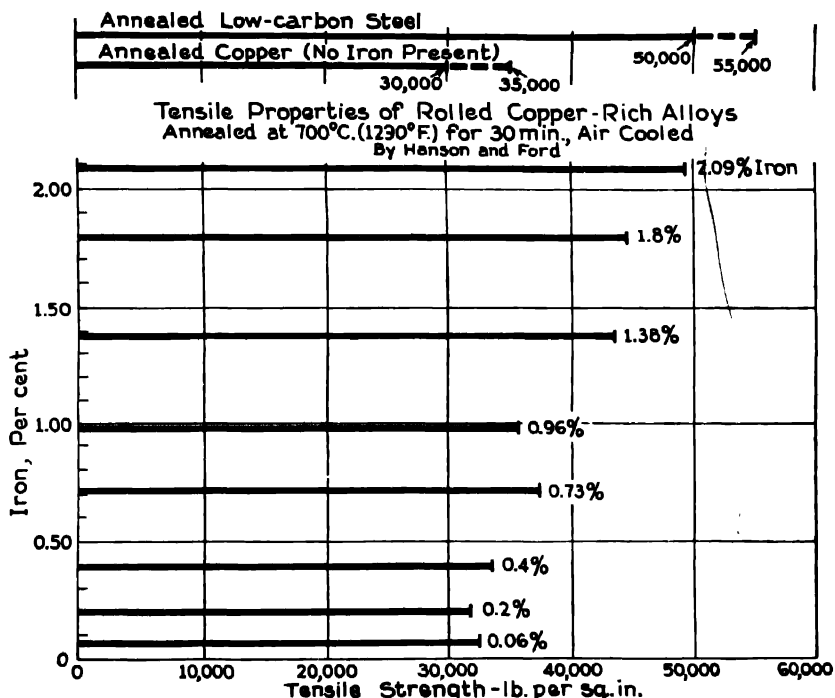
FIG. 20.3. Tensile strength of copper-rich alloys of copper and iron.

such a nickel, nickel-chromium, and molybdenum-chrome vanadium, can be copper brazed and afterwards heat treated to develop high strength and hardness.

The high-chromium steels (stainless varieties) do not lend themselves readily to copper brazing, because the chrome oxides are not reduced by ordinary furnace atmospheres at brazing temperatures. Silicon steels tend to oxidize even in most protective atmospheres and can be copper brazed only with use of a flux. The high affinity of copper for nickel results in poor penetration of copper into nickel or nickel-alloy lap joints. To overcome this, it is best to plate or coat the lapping surfaces with copper a few thousandths of an inch thick,
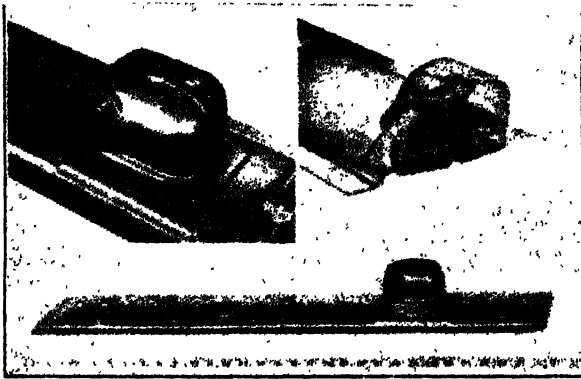
FIG. 20.4. Three views of a copper-brazed push-rod cover assembly for an automobile engine consisting of five parts.
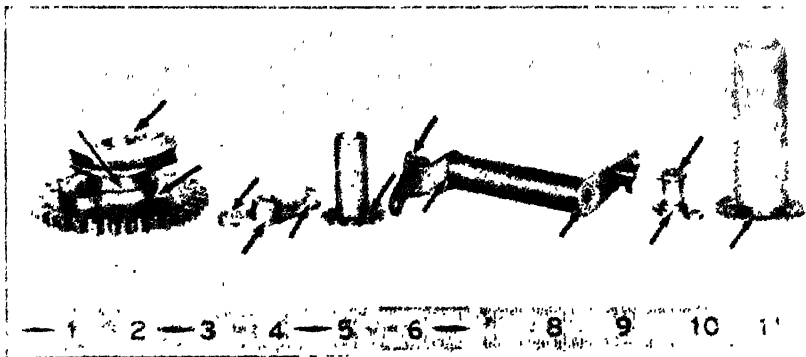
FIG. 20.5. Copper-brazed steel subassemblies for a cash register. Arrows indicate brazed joints.

FIG. 20.6. Copper-brazed steel fin condenser. Made entirely of stampings without tubing, except for tubular end connections, as illustrated by cutaway section.

or to allow more clearance in the joint, so that the fluidity of the filler may be retained until the joint is filled.

Several examples of assemblies fabricated by furnace brazing with copper are illustrated in Fig. 20.4 to Fig. 20.8.
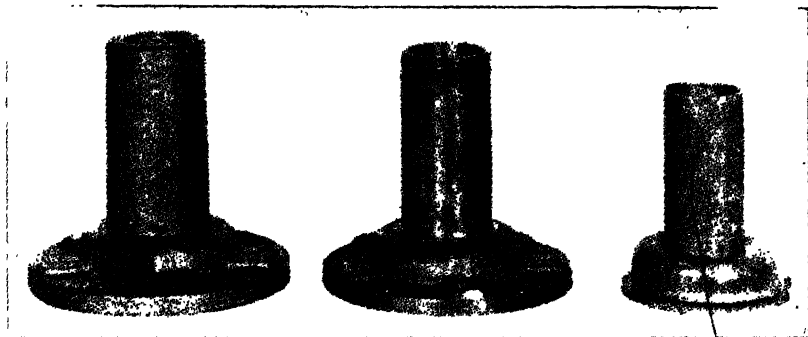
FIG. 20 7. Three designs of an automobile clutch-gear bearing retainer. Malleable iron casting weighing 2.5 lb (left); malleable iron casting machined weighing 1.5 lb (center); and new copper-brazed construction from steel tubing and a stamping weighing 0 5 lb (right).
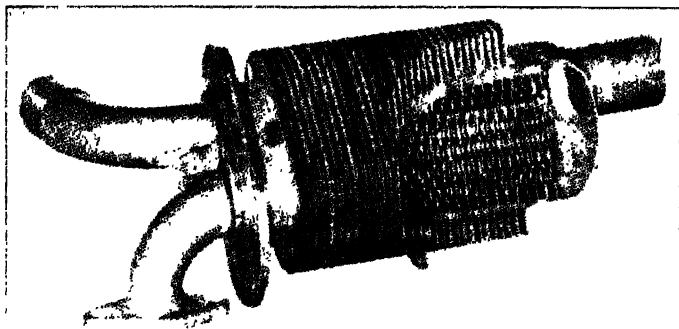
FIG. 20.8. Core (with part cut away) for automobile hot-air heater made of steel stampings and tubing, and copper-brazed.

20.4 COPPER ALLOYS FOR BRAZING

Common brass, called "spelter," was probably the first material used to make a brazed joint in ferrous material. Brass could also be used for copper and some copper-alloy parts, but it is seldom used any more, largely because of the objectionable distillation of the zinc during the heating period (zinc boils at 906 C). It has been replaced by nonfuming bronzes, which cost less than silver alloys, are especially

suitable when large quantities of filler metal are needed, and in which the high brazing temperature is not objectionable.

Tobin bronze, some silicon bronzes, and manganese bronzes work well, and are usually applied by hand with a torch. One type of application for them is on production where their strength at high temperature is desired. Their most common use is in salvage operations, particularly on castings. Table 20.1 gives the melting points of several common brazing alloys. Tobin bronze with a strength of approximately 50,000 lb per sq in. in tension is used on steel, cast iron, copper, and some alloys. The different brass manufacturers and brazing alloy vendors have different compositions which they recommend for certain applications. Nickel is an aid in brazing tungsten carbide, and several alloys on the market containing various proportions of nickel are recommended for this purpose. The bronzes are also used as a *surfacing material* when a better bearing surface is wanted on another material such as steel. A good brazing or welding operator can apply a thick layer of the bronze so that it can be machined to a good bearing surface.

A copper alloy containing 8 per cent phosphorus is marketed as Phos-copper. This alloy melts at 1400 F, flows at 1550 F, is processed at 1650 F, is self-fluxing on clean copper, can be used on copper alloys with flux, and must not be used on ferrous alloys. It is less expensive than silver-brazing alloys, particularly in the heavier gages, and is very satisfactory for joints where the members are heavy and rigid. But the phosphorus may diffuse into thin or flexible members and cause brittleness that is usually objectionable. This alloy and all copper alloys require clearances between parts to make a good joint.

20.5 SILVER BRAZING

Brazing processes that employ silver alloys are often referred to as "hard soldering" or "silver soldering," but "silver brazing" is the correct terminology. Pure silver is seldom used in industry as a brazing metal because alloys of silver, for example, silver and brass, have a lower melting temperature and better melting and flowing characteristics. The brazing alloy having the lowest melting point known contains silver, copper, zinc, and cadmium (see Table 20.1). This alloy is very fluid and less viscous than many other brazing alloys. Since zinc fumes, which may frequently be given off by these alloys, are objectionable in furnaces, zinc-free alloys, for example, silver and copper, are often used in furnace work.

Table 20.1 Copper and Silver Alloy Brazing Filler Metals

Type	Composition				Temperature, °F		Specific Gravity as Cast	Elec. Conductivity, % Cu	Remarks
	Ag	Cu	Zn	Others	Melt or soften	Flow			
1. Copper		100				1982		100	Tough-pitch or deoxidized copper flows freely on mild steel in hydrogen atmosphere without flux. Wire, sheet, or electroplated.
2. Brass		50–53	Rem.	0.05 Pb max	1600	1620			Brass-yellow color, used in rod, powder form, or in dip pot.
3. White spelter		Rem.	55–59	7–9 Ni		1600			Match in color for nickel-silver.
4. Phos-copper		92		8 P	1305	1385		3.6	Self-fluxing on copper. Gray color.
5. Yellow bronze		Rem.	42	0.5 Sn	1595	1625		25	Tobin bronze. Also used as rods for bronze welding.
6. Silver alloys	10	52	38		1450	1565	8.55	20.5	Low cost, malleable, higher temp. required than other silver alloys.
7.	15	80		5 P	1190	1300	8.45	14	Marketed as Sil-Fos. Lowest cost, self-fluxing on clean copper and silver. Not for Fe or high-Ni alloys.
8.	30	38	32		1370	1410	8.86		Satisfactory on brass. Used for high-temp. applications on squirrel-cage rotors, arc lights, and resistors.
9.	50	50			1435	1570			Used for furnace brazing.
10.	50	34	16		1240	1425	9.37	24.4	Marketed as ETX. High strength, malleable and ductile, low zinc. Good for large fillets.
11.	50	15.5	15.5	16 Cd 3 Ni	1195	1270			Marketed as Easy-Flo No. 3. For carbide tool tips and tool repair.
12.	50	15.5	16.5	18 Cd	1160	1175	9.49	23.9	Very fluid at brazing temperature; marketed as Easy-Flo No. 50.
13.	45	15	16	24 Cd	1125	1145			Lowest melting point, less cost than No. 12. Marketed as Easy-Flo No. 45.
14.	60	25	15		1260	1325	9.52		
15.	72	28			1435	1435	9.95	77.1	Eutectic zinc-copper alloy. Used for furnace brazing.

A silver-phosphorus-copper alloy, known as Sil-Fos, is very useful for brazing copper and copper alloys. The phosphorus content makes this alloy self-fluxing on clean copper and silver, but flux is needed on the copper alloys. This alloy should never be used on iron, steel, nickel, or high-nickel alloys since the phosphorus and the base metals form phosphorus alloys which are very brittle and may lower the strength of the surface layer to 40 per cent of its usual strength. Heat application must be controlled to avoid overheating when brazing copper, since brittleness from phosphorous penetration will be caused in these metals also. Sil-Fos is not as free flowing as the other silver alloys, and therefore does not flow into tight fits as well, but for most parts this difficulty can be avoided by preplacing pieces of the alloy in joints between flat surfaces.

Some silver alloys are more fluid (less viscous) than others. This means that with proper technique and the proper alloy, fillets can either be practically eliminated around a joint, or liberal-sized fillets may be obtained. If the proper alloy and technique are used, dressing or smoothing of the joint surfaces should seldom be necessary. When there may be danger of galvanic corrosion, the tendency may be minimized by eliminating fillets so that only the thin edge of the alloy is exposed.

For brazing copper, brass, and bronze with alloys high in silver, more clearance should be allowed in the joint because the free alloying between these base metals and the silver will cause the latter to change in composition before the joint is completed. This change may reduce the fluidity and the melting point of the filler alloy to such an extent that it is difficult to fill the joint.

The 18-8 type stainless steel can be silver brazed, but it should be remembered that the brazing temperature is in the carbide-precipitation temperature range for this material, and if corrosion resistance is wanted, a stabilized grade of 18-8 stainless steel should be specified.

High-nickel alloys, such as Nichrome resistance wire, have a peculiar characteristic. In the fully annealed condition they braze very satisfactorily. But, when under strain, silver should be kept away from them because the molten silver alloy will penetrate rapidly along the grain boundaries and sever the wire.

20.6 ALUMINUM BRAZING

Aluminum-brazing alloys are used only for the brazing of aluminum. As with any other metal, the brazing of aluminum requires an alloy with a melting point lower than that of the parent metal

and a flux which will dissolve the oxides at brazing temperature. Furnace and torch heating were the first procedures that were developed and applied to production, but the chemical bath method has shown considerable promise. For furnace brazing the best filler metal and flux depend on the parent metal as shown in Table 20.2.

Table 20.2   Alloy Compositions, Fluxes, and Filler Alloys for Aluminum Brazing *

	Filler Material	*Flux*	*Furnace-Brazing Temperature, °F*
Parts			
2S, and 3S	X-718	33	1160–1185
53S, and 61S	X-718	33	1160–1185
Brazing Sheets			
No. 1—3S with coating 1 side	..	30	1160–1185
No. 2—3S with coating 2 sides	..	30	1160–1185
No. 11—3S with low temp. coating, 1 side	..	30	1090–1140
No. 12—3S with low temp. coating, 2 sides	..	30	1090–1140
No. 21—Eq61S with low temp. coating, 1 side	..	30	1090–1120
No. 22—Eq61S with low temp. coating, 2 sides	..	30	1090–1120
Castings			
406	X-716	33	1160–1185
X612	X-716	33	1160–1185
Torch Brazing			
2S, 3S, 53S, 61S	X-716 wire	33	..

* Prepared from information supplied by the Aluminum Co. of America. Designations are from that company.

No satisfactory brazing technique has been devised for such aluminum alloys as 11S, 14S, 17S, 24S, 27S, or 56S at the present time.

The filler metal is usually applied in the form of wire or sheet-metal washer as is common practice with other metals. A novelty, however, is offered here in that sheets are available with coatings of the brazing material on either one or both surfaces. These are called Brazing Sheet. These coats are more than simple "pretinning," as there is enough brazing alloy to form fillets. Parts formed from this brazing sheet are brazed by merely coating the area at the joints with flux and heating to the proper temperature in a furnace.

The temperature required for brazing aluminum is above the recrystallization temperature, so that any of the cold worked alloys are annealed by the operation. Design strength figures should be based on the annealed strength of the alloy. Sometimes, however, the 61S or 53S alloys are quenched upon removal from the brazing furnace, and the parts can then be aged to develop, by precipitation, optimum hardness and strength in the parent metal and across the joint. The same results can be obtained by solution heat treating and quenching the part in a separate operation after the brazing operation.

It is important that aluminum joints be thoroughly cleaned of all grease, oil films, and dirt preceding the brazing operation. If a part has been annealed for forming, it should be cleaned by an etching method.

Corrosion resistance of aluminum brazed joints is comparable to the resistance of welded joints in the same alloy.

A valuable paper, The Flow of Metal in Brazing Aluminum, by M. A. Miller, was published in the *Welding J.*, pp. 472S–478S, October 1941, from which the following is quoted:

Because the oxide on aluminum surfaces is generally displaced rather than completely dissolved by the flux, it is usually advantageous to feed the alloy from one side of the capillary; this tends to overcome flux entrapment and porosity because the molten alloy has a better opportunity to sweep out the flux and particles of oxide and other surface impurities. A fairly large reservoir at the edge of the joint is generally desirable, so that the brazing alloy will have a chance to puddle and feed into the joint.

In the use of the new duplex aluminum brazing sheet . . . the situation is considerably different, for example, than the use of copper plating on steel. In the latter case, a hydrogen atmosphere is generally employed as a "flux," no flux-entrapment problem ensues, and long laps can readily be made. In the case of duplex brazing sheet, a flux being required, long laps are not generally permissible. In fact, the best joints are produced from line contacts; thus, the alloy coating flows vertically up or down or horizontally toward the nearest capillary space—and this, through surprisingly long distances—to fill the joint and produce a fillet of a size related to the type of coating, the thickness of the coating, the distance of flow, the temperature, and the time.

Capillary traps (enlargements in the capillary to overcome the effect of surface tension) are of little use in the brazing of aluminum. There are several reasons for this. The aluminum brazing alloys are somewhat more viscous than some of the non-aluminum brazing alloys, though they are still free flowing, and hence will bridge substantial gaps. Secondly, the aluminum brazing alloys, being intersoluble with the aluminum base metal, will exhibit surface creeping or flow; this process also results in a disregard for traps.

20.7 JOINT DESIGNS

Since the filler metal is normally weaker than the parts joined by brazing, the strength of a brazed joint usually depends on the amount of unchanged brazing alloy left in the joint in the form of à thin coating. This depends, in turn, on the composition of the filler and the parts, the time and temperature of the brazing operation, and the clearance in the joint. Provided the gap is not too great for the
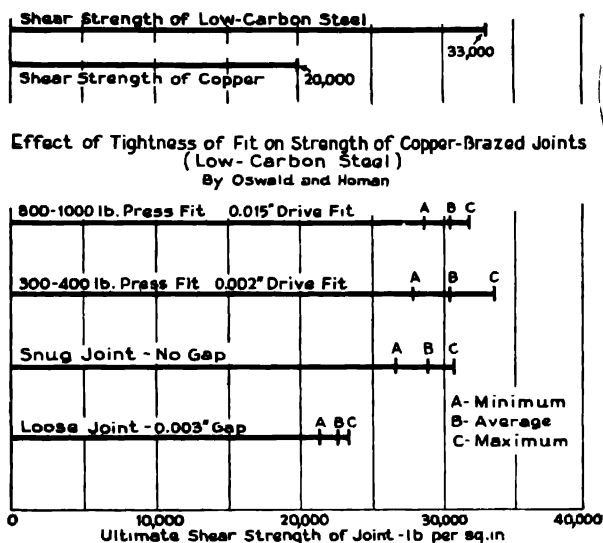
Fig. 20.9. The effect of fit tightness on the strength of copper-brazed joints made from low-carbon steel.

alloy to fill it, the strength of the joint approaches the strength of cast filler alloy as the gap is increased in any type of joint. Figs. 20.9 and 20.10 illustrate the effect of clearance on the strength of joints brazed with copper and with silver alloy. The clearances usually recommended for each of the four types of brazing alloy are given in Table 20.3.

The three fundamental types of joints are butt, scarf, and lap or shear (see Fig. 20.11a, b, c). Each may be used with flat, round, or tubular members. Butt joints are satisfactory when carefully made, and are sometimes the only way a joint can be assembled. An important use of the butt joint is in the production of hollow-ware articles which are made by stamping half sections from sheet metal and joining them. The edges must be square and straight to main-
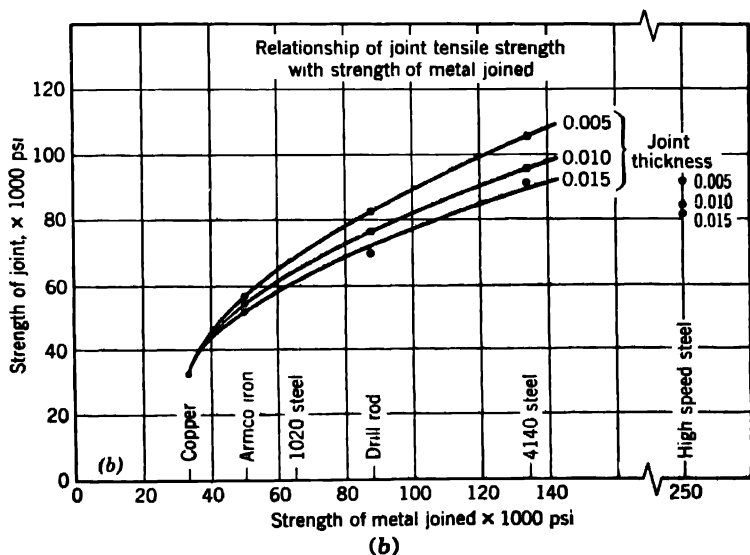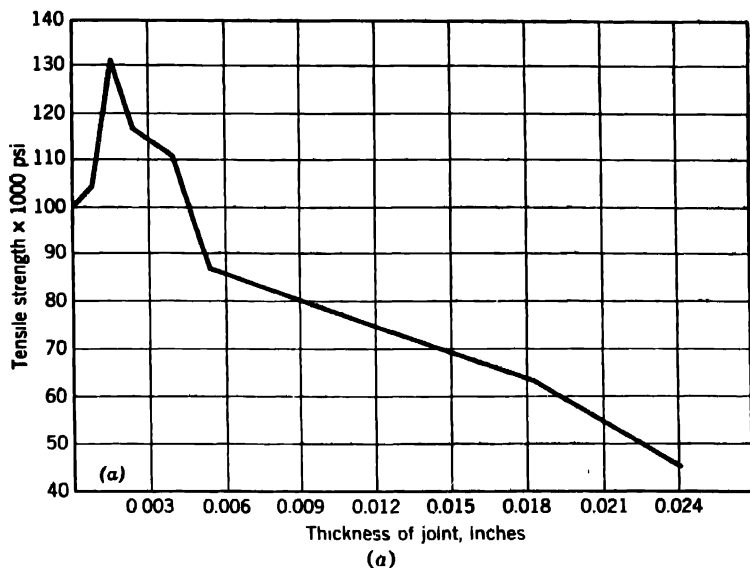
FIG. 20.10. (a) The effect of joint thickness on the strength of silver-brazed butt joints, stainless-to-stainless steel using Easy-Flo (No. 50). (b) Tensile strength of Easy-Flo (No. 50) joints vs. strength of parts joined for three different joint clearances. Shear strengths average 37,000 for Armco iron joints to 43,000 for high-speed steel. Short-time strength begins to drop off over 200 F. Long-time tensile creep strength is usually from 5000 to 10,000 psi at 400 F, and less for higher temperatures.

Table 20.3   Capillary Clearances for Various Brazing Systems

Brazing Alloy	Base Metal	Recommended Clearance, in.
Copper	Ferrous	Press fit,* when brazing in a protective atmosphere
Copper	Stainless steel	0.0015 when brazing in a protective atmosphere
Silver alloys	Ferrous	0.0015 to 0.002
Silver alloys	Stainless steel	0.0015
Silver alloys	Copper, nickel, and their alloys	0.002 to 0.003
Aluminum alloys	Aluminum alloys	Lap joints ¼ in. or less 0.006 in. to 0.010 in. clearance. Over ¼ in., 0.010 in. and up clearance †
60-40 Brass	Iron and copper	0.030

* For this purpose a good general rule to follow is to call for a maximum permissible press fit of about 0.001 in. per in. of diam, allowing whatever tolerance the shop needs in the other direction.

† When using Brazing Sheet and when the coating is in the joint, the surfaces should make contact since the coating provides sufficient clearance.

tain a uniform space between the members and they should be held closely together to insure even flowing of the filler metal by capillary action. When butt joints are necessary, greater strength can be obtained if a step or scarf type of joint (Fig. 20.11*d* and *b*), can be formed. The butt strap shown at (*e*) forms more of a compromise. The joint illustrated in Fig. 20.11 (*f*) is not recommended.

Lap joints (Fig. 20.11*c* and *h*) are preferred for all types of brazing when high strength or pressure tightness is required. By increasing the amount of lap (area of the joint), any safety factor against failure may be obtained. When joining flat sheets or strips of copper, brass, or Everdur with silver alloys, a length of lap equal to the thickness of the sheet may give a joint as strong as the metal joined. However, for equal electrical conductivity of joints in copper tests have shown that a lap equal to 1½ times the thickness is the safe rule to apply when using Sil-Fos.

The large number of factors that affect the strength of a brazed joint make it very difficult to give a precise formula for determining the length of a shear or lap joint for some required strength. Fortunately, however, the strength of brazed joints is great enough that ample factors of safety can be provided and the length of lap still be kept within the limits of good and economical design. The following simple formula can be used for determining length of lap (depth of shear) on either tubular or flat joints.
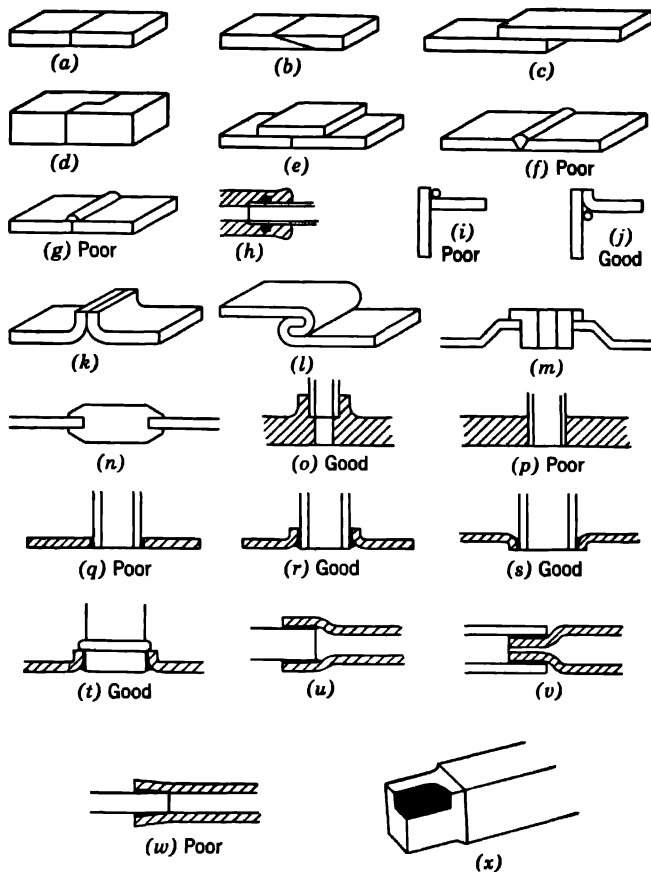
FIG. 20.11. Examples of good and poor joints for brazing, particularly with copper and silver alloys.

$$X = \frac{YTW}{L}$$

where X = length or depth of shear, T = tensile strength of weakest member, W = thickness of weakest member, Y = factor of safety, and L = shear strength of brazing alloy.

As an example, assume 50,000 lb per sq in. as the strength of the brazing alloy, and a factor of safety of 10. The length of lap for a copper tube with 0.064-in. wall thickness to be brazed in a pipe fitting (assuming the copper tube has a tensile strength of 33,000 lb per sq in.) is

$$\frac{10 \times 33,000 \times 0.064}{50,000} = 0.423 \text{ in.}$$

This equation applies only to the type of lap joints that distributes the load over the whole area. The type of lap shown in Fig. 20.11 (*j* and *k*) is better than the joint shown at (*i*), giving greater strength and leak tightness, but mechanical load (tension) is all concentrated at one surface and so produces a tearing action which differs greatly from the condition existing in (*c*), (*e*), (*h*), or (*o*). The hub on the
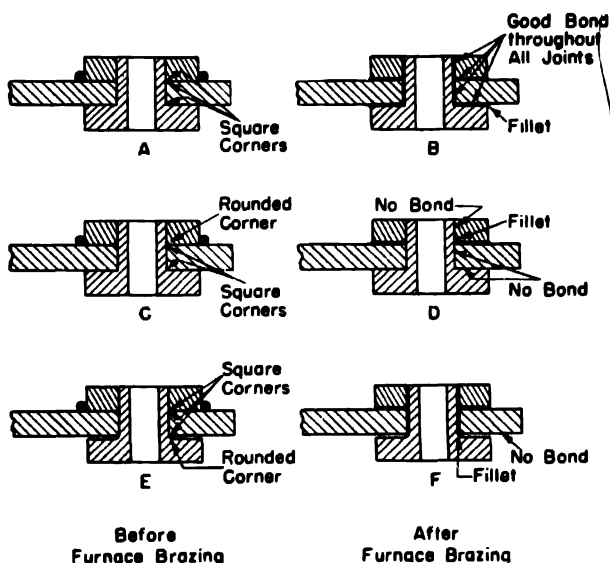
Fig. 20.12.   Effect of gaps in the joint on the flow of brazing alloy.

flange in (*o*) is recommended as an aid in heating. This is more important on heavy flanges. Without the hub, the whole flange must be brought up to temperature to make a brazed joint. This might be satisfactory in a furnace, but most piping jobs are heated with portable equipment, and heating the whole part would be inconvenient.

The importance of clearance between parallel surfaces has been stressed but the same rule must be applied if filler metal is to flow around corners. Fig. 20.12 illustrates how gaps in the joint may block the flow of brazing alloy through the joint. A square edge on the hole prassed tightly against a radius on the fitting as at E, Fig. 20.12, would similarly stop the flow of a silver alloy, even though the clearance is right on each side of the corner.

It is very difficult to obtain a good joint that seals a cavity because of the pressure established during heating as the air attempts to expand. Special difficulty is encountered if a large volume of air must be heated. When possible, such cavities should be vented (Fig. 20.13).

If a hermetic seal is to be obtained, use of an eutectic alloy will provide quick setting and diminish the duration of the mushy period when leaks could occur.

When making flat joints in cable, the pressure applied may cause the strands of the cable to

Vent Hole

Flat Side on Tenon Leaves Vent

Fig. 20.13. Venting of cavities.

spread. One of the many different methods used to control this is illustrated in Fig. 20.14. A piece of copper strip is formed to encircle the strands. Many such joints are brazed in spot welders. The terminal is laid on the lower electrode, the cable carrying the ring or clip is placed with the opening next to the terminal but with a strip of Sil-Fos between. When pressure is applied the clip is flattened, and the opening allows Sil-Fos to flow into the strands, making a solid connection. Larger cables that require longer heating are sometimes enclosed in pieces of regular copper tubing. The tubing

Fig. 20.14. Silver-brazed lead and terminal assembly for a transformer before and after brazing.

will flatten to some extent in the brazing operation if brazed by an electrical-resistance method, but many times is flattened in advance as a separate operation. When tubes are used, the filler is fed into the end of the strands by hand. Just enough is used to seal all the

strands at the end without allowing excess alloy to creep back to stiffen the cable beyond the terminal. Another common method of binding the strands of a cable is to wrap them with wire or copper strip—0.010 in. by 0.125 in. copper has been used for this purpose. The flat binding not only looks better than the wire binding but with electrical-resistance heating makes better contact with the electrodes to carry both electricity and heat. However, these wrappings are not as neat as the clips and tubes described.

20.8 JOINTS PRELOADED WITH BRAZING ALLOY

One of the most foolproof methods of placing the brazing alloy for heating is to insert it in wire form in grooves, as shown in Fig. 20.15.

Wire Ring
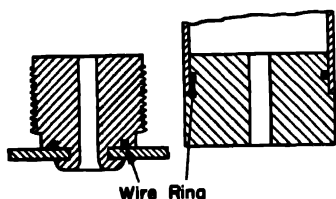
Fig. 20.15. Brazing wire inserted in a groove in the joint.

This same method is employed in pipe fittings to be used with copper and brass pipes. The assembly illustrated on the left is ideal for copper brazing in the controlled-atmosphere furnace, but some clearance would have to be provided for alloy fillers. Fig. 20.16 illustrates several other ways of applying filler material in wire form. The staking is suggested especially to hold the parts for the furnace heating. Heat-resistant supports, expanding, riveting, pinning, and spot or tack welding may be similarly used to hold parts during brazing. Fig. 20.17 shows two successful methods of using copper foil in furnace brazing.

The more common types of assemblies used in the brazing of aluminum are illustrated in Fig. 20.18. These show the use of wire, coated brazing sheets, and one assembly using washers. As explained before, since aluminum-filler metal is highly viscous, a tapered pipe fit is used. The filler for this fit would be a ring of wire. It is important that such wire rings hug the vertical surface, and it is preferred that they grip the vertical surface tightly enough to hold them off the horizontal surface. This assures wetting of the vertical surface to form a good fillet, whereas if the ring lies on the horizontal surface, it may melt and flow away without bridging the joint. The taper fit is to be avoided with other kinds of filler materials.

Use of Hydrides. A new method of brazing nonmetallic materials such as ceramics, carbides, sapphires, and diamonds to metals has been developed and should find ready application as a method of
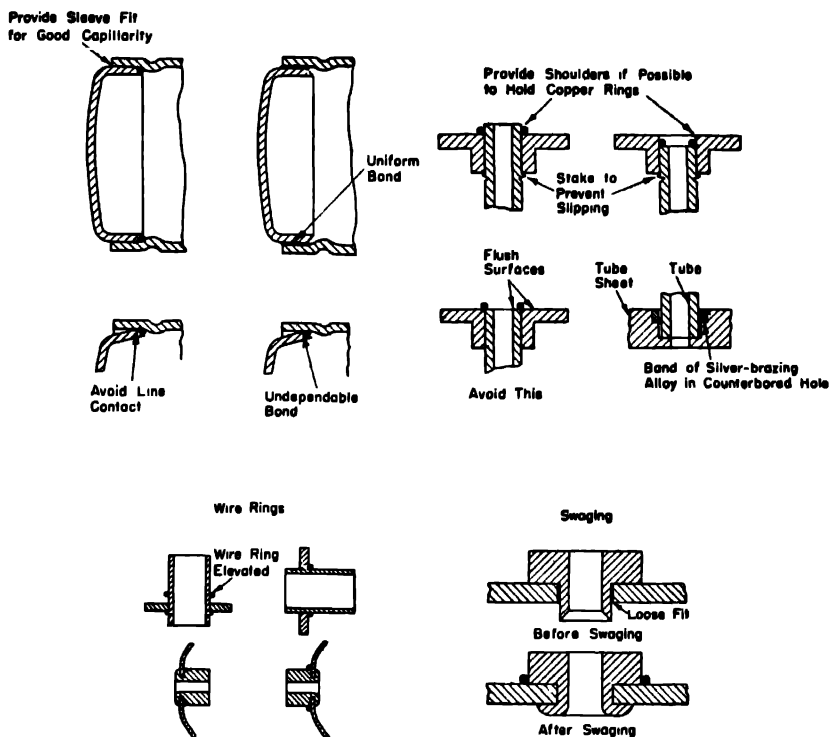
FIG. 20.16.   Methods of applying brazing material in wire form.

producing tools and many other products.   This brazing process is a one-step operation and is completed in controlled atmospheres or in vacuum without the use or application of fluxes.   It produces an exceptionally strong bond which often exceeds the strength of the nonmetallic material.

The technique consists, briefly, of producing a brazing alloy that will wet and bond both metals and nonmetals by either of two means: (1) by the use of hydrides of titanium, zirconium, tantalum, or columbium; or (2) by the use of special brazing alloys.

In the former, the general procedure involves coating the surfaces to be brazed with a thin film of the metallic hydride.
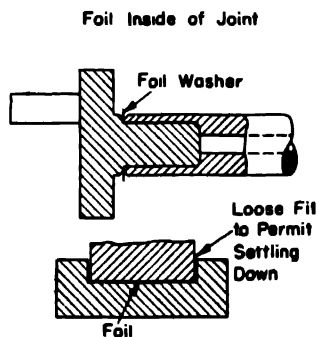
FIG. 20.17.   Two methods of using copper foil in furnace brazing.

A water paste or a nitrocellulose-solution binder seems to work equally well in producing a thin, uniform coating of the hydride. A piece of suitable solder is then placed in contact with the hydride-coated surface, and the material is heated to approximately 1830 F in a vacuum of approximately 10^{-4} mm of mercury or better, or in an atmosphere of pure hydrogen or a pure (or sometimes commercial)
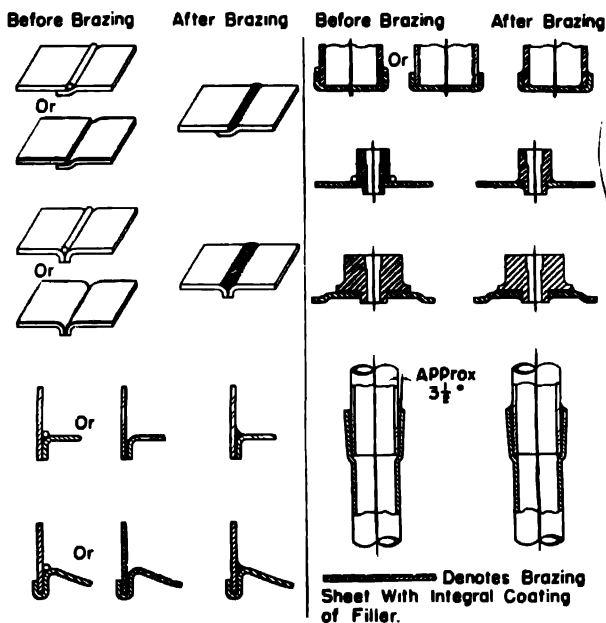
Fɪɢ. 20.18.   Joint designs especially for aluminum brazing.   (*Courtesy Aluminum Co. of America.*) *

inert gas.   When the proper temperature is reached, the brazing alloy will melt and flow over the hydride-coated surfaces in a manner somewhat similar to conventional furnace brazing.   Copper-silver eutectic solder, pure silver, and pure aluminum have been used as solder, with excellent results.

The special brazing alloys have been prepared from both the metal hydrides and the pure metals.   Zirconium hydride can be heated in vacuum at approximately 1470 to 1830 F to remove the hydrogen, leaving a relatively pure zirconium metal powder.   This partially sintered metal powder can be exposed to air and then used in a manner similar to zirconium hydride to produce an equally good braze. Alloys of aluminum and zirconium, of silver and zirconium, and of

* From *Technical Data Bulletin* 3 of Aluminum Co. of America.

aluminum, silver, and zirconium have been prepared and show good wetting and bonding properties.

20.9 BRAZING FLUXES

A flux is a chemical agent which, when properly applied and adapted to the particular situation, will aid the brazing operation in three ways: (1) it will coat the surfaces of the joint to protect them from oxidation by the atmosphere while heating; (2) it will dissolve any oxides that have formed on the surfaces of the metal parts; (3) it will lower the surface tension of the molten alloy to allow it to flow more freely into the joint. Brazing fluxes are not really active to perform functions 2 and 3 until the flux has melted.

It is emphasized that fluxes are not cleaners. At times, a fluid active flux will function to produce a good joint under the handicap of dirty surfaces, but fluxes are not designed to remove oil, grease, carbon, paint, or many other kinds of dirt. Any oxide or dirt on the surfaces of the joint before the flux is applied only increases the chance of obtaining a poor joint. To assure the best results in the brazing of a joint, or to·obtain uniformly good results in a series of joints, have the joint surfaces and adjacent areas clean and bright when the flux is applied.

Borax, which is the old standard flux for brazing, exists in two forms. Ordinary borax is in the crystalline form, containing considerable moisture in the form of water of crystallization. When heat is applied to this, it puffs up and rolls around so that it furnishes little protection to a joint being brazed. The use of amorphous, or fused, borax avoids this trouble, as it melts quietly. Its usefulness, however, is limited in two ways: (1) since it melts at approximately 1400 F, it is serviceable only with the higher-melting-point filler metals; and (2) it does not dissolve the oxides of many of the alloying elements such as chromium, molybdenum, silicon, and tungsten, so is serviceable only on the common steels, brasses, and bronzes.

Most brazing fluxes are mixtures compounded to obtain a lower melting point than that of borax, and a more active solvent for the refractory oxides. The type of flux needed is determined more by the base metals than by the filler. A flux stronger than necessary should not be used, since the salts and fumes may be toxic and forced ventilation may be required to remove them.

The dry-powder fluxes are common, but they do not furnish as complete service as the paste fluxes. Paste fluxes can be brushed over the joint before heating, and thereby furnish some protection

throughout the heating period. Paste fluxes also can usually be used in joints heated by electric-resistance methods, whereas the electrical insulation resulting from the use of dry powder prevents its use in such applications. Paste fluxes are easily applied to other than horizontal surfaces. A gas torch also blows the dry powder away unless the surfaces have been heated to the point where the flux begins to melt and then sticks. Often, the end of the rod, or ribbon, of filler metal is heated so that the powder sticks when it is dipped into the can of flux. Sometimes the only flux applied to the joint is applied along with the filler metal in this way. Although it is satisfactory on easy jobs, it is recognized as not the most effective way to handle a difficult situation.

Corrosion is a problem that seems always to be with us. Any residual flux that remains on the work after the braze is finished is apt to absorb moisture from the air and start corrosion the same as table salt would. The preferred practice, therefore, is to remove all flux residues.

A furnace atmosphere of hydrogen also acts as a flux to reduce the oxides of the iron, copper, and some other metals, but when the hydrogen does not function to reduce more refractory oxides, one of the regular brazing fluxes must be applied to the joint for this purpose. The salt bath described later as a heating method also serves as a flux. Aluminum requires special fluxes.

20.10 METHODS OF HEATING

Almost any heating device that will raise the temperature of the joint to the necessary brazing temperature can be used, but economics and results obtained do place a few limitations on the choice of equipment.

The heating problem may be outlined by three requirements:

(1) Both members, or surfaces, of the joint must be heated above the melting temperature of the filler metal before it will wet and flow to make a good joint. The quicker the inner surfaces can be heated to the necessary temperature without overheating an external surface, the more satisfactory is the whole result. This problem is illustrated by trying to furnace braze a light aluminum section to a heavy section. The light section may overheat and slump before the heavy section reaches brazing temperature. In torch brazing the flame can be concentrated on the heavier piece to reduce the time required, thus limiting oxidation and perhaps other trouble.

(2) The oxidizing or reducing influence of the heating method or atmosphere upon the joint surfaces, flux, or filler material is im-

portant because it may have a marked effect upon the results. For example, any hydrogen present at the red-hot surfaces of ordinary tough-pitch copper will probably have an embrittling effect. Otherwise, reducing atmospheres are always preferred.

(3) The two parts being joined must be held in proper relation to each other during both heating and cooling, and must not be moved until the alloy is solid, otherwise the filler metal will be granular with cracks. Some assemblies are best heated in jigs or stationary equipment; other jobs, such as piping on board ships, require the most portable equipment.

No one heating method is best for all brazing applications. It is therefore worth while to review the more common methods of heating, which include furnace, torch, metal bath, chemical bath, arc, induction, and resistance heating.

20.11 FURNACE BRAZING

The feature that makes a furnace so popular for brazing is the controlled atmosphere that is almost universally used. A neutral gas may be used for brazing joints in copper without embrittling or oxidizing the copper. But for the best results, a reducing atmosphere in an electric furnace is usually preferred (copper parts are then made from deoxidized copper). Any of the brazing alloys may be used in a furnace, and the low-temperature alloys have been used to advantage on special jobs; but since hydrogen does not reduce the oxide of zinc, the filler metals most popular for furnace work are either pure copper or one of the copper-silver alloys, except for joining brass, which requires a flux.

The furnace is best adapted to the brazing of small high-production assemblies or to units involving many joints. For such parts, it gives a high production rate since many joints are brazed at one time. Complicated assemblies are sometimes best heated in a furnace to equalize thermal stresses, since progressively heating one spot after another in a structure will sometimes result in bad distortion, or the cracking of brazing alloy while it is still hot. Other benefits that may result from furnace brazing include the following: (1) reduced production costs because of savings in time, material, rejections, or inspection; (2) uniform tightness as a result of uniform distribution of brazing metal, and through accurate control of time, temperature, and furnace atmosphere; (3) little or no distortion, with freedom from localized strains; (4) excellent appearance with clean, bright surfaces and smooth fillets at joints; and (5) flexibility through ability to braze light parts to heavy ones and to join unlike metals.

There is a variety of furnace designs (e.g., box type, mesh belt, and roller hearth conveyor types) to suit the requirements (see Chapter 17).

Hydrogen gas at temperatures above 800 C will reduce the oxides of carbon, steel, and copper, and when copper is heated above its melting point in contact with carbon steel in a reducing atmosphere,
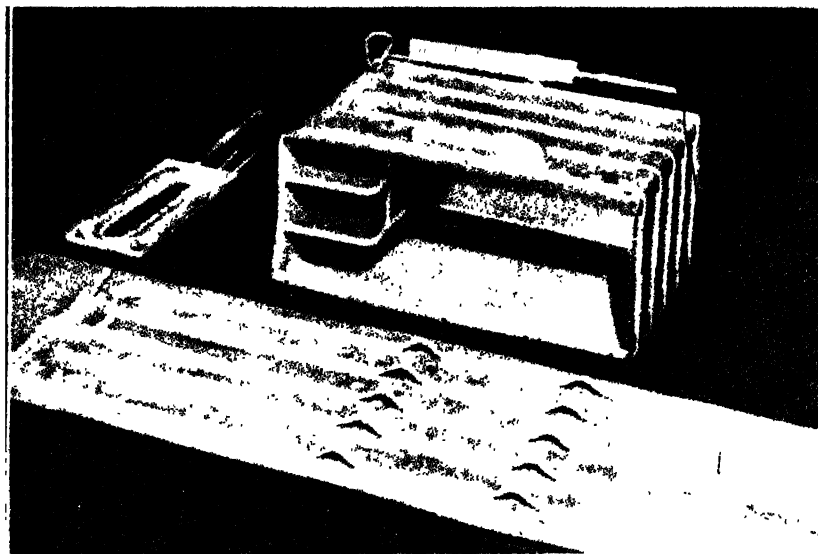

Fig. 20.19. *Below:* aluminum tubing 0.035 in. wall furnace brazed to aluminum sheet 0.036 in. thick. *Upper:* all-aluminum refrigerator evaporator made from brazed sheet and tube assembly. *Right:* separate brazed shelf.

the copper will flow freely on the surface of the steel and will alloy with it. Furthermore, in the presence of a reducing atmosphere, the capillary action of liquid copper between two pieces of steel in close contact is very pronounced. Since the process must be carried out in a hydrogen or other type of reducing-gas atmosphere, the work is limited to assemblies that can be heated in a furnace. It is true that copper brazing can be carried out with the use of suitable fluxes in air, using a gas torch or other methods of heating; but, owing to the high temperature required for melting copper and to trouble from oxidation, it is seldom done. .

In copper brazing, the assemblies are put together, and the parts located by means of spot welding, pressing, swaging, etc., to prevent slippage or moving of the assemblies while the copper is in a liquid

state. Copper, in some form, such as wire, is applied near the joint and the complete assembly is then passed into an electric furnace at a temperature of approximately 1140 to 1150 C. After the copper melts and flows, the assemblies are passed into a cooling chamber where the copper-iron alloy formed at the joint solidifies and the whole parts cool to approximately room temperature.

The furnace brazing of aluminum requires that a special flux be applied in the joints as they are assembled. The melting point of these filler metals is so near the melting point of the parent metals that care must be exercised not to melt the filler metal or thin parts of the assembly before heavy sections are up to temperature. On the other hand, slow heating usually results in excessive oxidation or an interdiffusion of the filler and base metal before the filler flows freely. In designing for brazing, it is poor practice to combine a large range of thicknesses in the same assembly (see Fig. 20.19). Material 0.006 in. thick will reach brazing temperature in a few minutes, whereas it requires 40 to 45 min for ½-in. material to reach brazing temperature. A period of 2 to 6 min at the brazing temperature is required to melt the filler metal and flow it into the joints.

20.12 TORCH BRAZING

In the hands of an experienced and skillful operator, the gas torch is probably the handiest and most universally applicable method of heating. A combination of fuels, such as oxyacetylene, oxyhydrogen, oxy-city gas, or natural gas are most commonly used. The heat is ap-

Fig. 20.20. Torch tips for silver brazing.

plied to the parts away from the joint in such a way as to bring both members up to the brazing temperature uniformly. A neutral or reducing flame is always used, except when brazing tough-pitch copper; here an oxidizing flame is used to avoid embrittlement. A multiple tip torch is often used to speed operations and obtain uniform heating. A variety of such tips is shown in Fig. 20.20.

20.13   METAL-BATH BRAZING

The metal-bath brazing process is a dip process wherein the filler metal is obtained from the molten metal bath. For a number of reasons, it is confined to joining comparatively small work such as joints in wire.

20.14   CHEMICAL-BATH BRAZING

This method of heating, also known as the salt bath, requires that the assembled parts, with the brazing alloy in place, be carefully supported by suitable jigs. The entire assembly is then dipped into a bath of molten flux held at a temperature somewhat above the melting point of the filler material. It has the advantage of heating the members quickly and at the same time of providing protection from the oxidizing effect of the atmosphere. Temperature is easily controlled in this process, which has shown considerable promise for the brazing of aluminum. The size of the bath will depend upon the size and weight of the assemblies that are to be brazed, but, in general, these baths should be large enough so that there is no appreciable drop in the temperature of the bath when the assembled units are immersed.

20.15   ARC BRAZING

This is a process wherein the heat is obtained from an electric arc formed between the base metal and an electrode or between two electrodes. The carbon arc is perhaps the most common form, but the process is used very little in brazing.

20.16   INDUCTION HEATING

Application of this type of heating has been limited by the equipment available, but developments are leading to more general applications, including brazing and soldering as well as other heating jobs. It is the one method of heating that always generates all the heat within the parts being heated, in contrast to the methods that heat from the outer surface. Many brazed joints are of a type to which induction heating is readily applied. For such joints, one or more of the following advantages may be obtained: (1) short heating time; (2) lower costs; (3) semiskilled operators can be used; (4) heat is confined to a small area around the joint, and the assembly can be easily handled by workers; (5) small amount of scale; (6) the heating operation can be controlled automatically to produce uniform results; and (7) no hazard of flame.

Motor-generator sets, which have been developed to supply power at frequencies up to 12,000 cycles per sec, have a wide application in the heating of relatively large steel parts. Such low frequencies, however, are not economical for the heating of copper, aluminum, and small, irregularly shaped brass and steel parts. A spark-gap oscillator has been developed to supply higher frequencies for heating these parts, but it is limited to about 2000 kilocycles and approximately 15 kw power output. Electronic heaters (vacuum-tube oscillators) to supply power at 550 kilocycles are now developed and built to industrial standards and their use and applications are expanding rapidly.

The fundamental principle in heating a part to be brazed is to create an alternating magnetic field into which the joint may be placed. The joint is positioned in the center of a specially fitted coil, and high-frequency alternating current is applied for a definite time cycle. For best results the coil shape and size should match the assembly to be heated. A coil is easily made from copper tubing which carries its cooling water.

To achieve high production in induction-brazing operations, more than one joint can be heated at a time by connecting a number of coils in series. Figure 20.21 show such an installation for brazing the four terminals simultaneously to the low-voltage conductors of a transformer. The installaton forms a station on the production line.

Any joint properly designed for brazing and of a shape such that an induction coil can be economically designed around it can be successfully induction brazed. When possible, the joints should be designed for pre-assembly with the brazing alloy in position prior to heating. Usually it is important that the alloy as well as the parts be thoroughly fluxed. Figure 20.22 shows several types of joints that have been successfully induction brazed and illustrates the application of the heating coils. The same capillary clearance must be allowed in joints such as *A*, *B*, *C*, and *K* as has been discussed before and as listed in Table 20.3. In press-type joints such as *D*, *F*, and *J* an allowance of 0.0005 to 0.001 in. is sufficient.

The close control of temperature-time cycles often makes it possible to complete a joint without affecting the finish on the parts. Silver-plated parts have been brazed successfully without harming the plating. Even with copper the oxide film is very light, on account of the speed of heating and cooling. Flux will protect the surface near the joint when a bright surface is desired after brazing. With

the better installations, power is applied by a pushbutton and stopped automatically by a timer.

FIG. 20.21. Installation for induction brazing four terminals to the low-voltage conductors of a transformer. The induction furnace is at the top.

20.17 RESISTANCE BRAZING

Resistance brazing is an electric brazing process wherein the heat is obtained by passing an electric current through the parts being brazed. There are two rather distinct types of equipment used: (1) that using carbon blocks, and (2) regular resistance welding machines.

When carbon blocks are used for electrodes, they are heated to a bright temperature by their electrical resistance, and most of the heat obtained in the joint is conducted in from the hot carbons. The equipment may be either stationary or portable. Figure 20.23 shows a complicated assembly being brazed in a stationary press using carbon blocks for heating. The working faces of the press are water cooled. Figure 20.24 shows a joint gripped in portable equipment for brazing. Such an outfit usually employs 5, 10, or 20 kva high-current low-voltage air-cooled transformers, but smaller or larger and water-cooled transformers are used for certain jobs.

Resistance-welding machines, with their accurate timers, give fine results and high speed on many small-part assemblies. They are especially useful with assemblies of copper and copper alloy parts

where Sil-Fos can be used, such as putting terminals onto cables. Figure 20.25 shows how a small piece of copper is placed to confine the strands of the cable brazed to the head of a brass screw. Sil-Fos
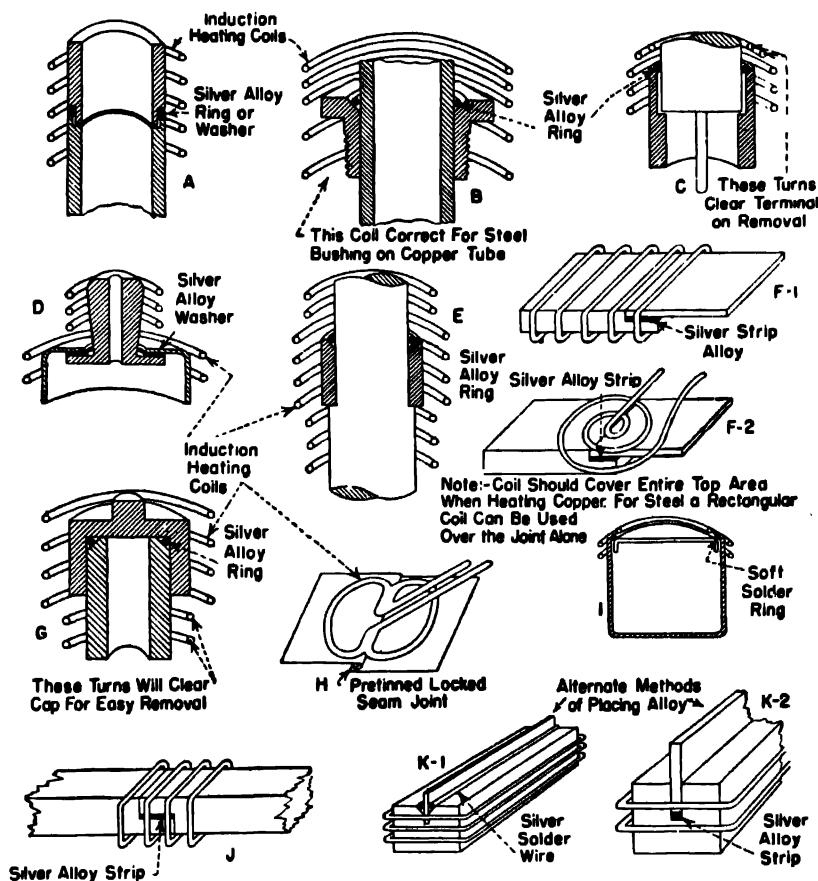
FIG. 20.22. Joints for induction brazing, and the application of the induction heating coils.

with a small amount of paste flux is used on brass. Pressure is maintained on the joint until the alloy is solid; then, as soon as pressure is released, the hot joint is quenched in water to remove the flux and save the insulation. The result is a clean, neat joint with a minimum amount of heat effect. With certain size sections of copper cable, this is the only way in which satisfactory silver-brazed joints can be made without burning the insulation or unduly annealing the copper.

Such machines are equipped with electrode surfaces of tungsten or some high-tungsten alloy backed by water-cooled copper, so that a great deal of the heat is generated in the joint. The water cooling produces quick solidification of the alloy. The heating time for small

FIG. 20.23. Four braid groups in clips being silver-brazed simultaneously to a fabricated conductor. Carbon blocks are used for resistance heating.

FIG. 20.24. Portable electric-resistance brazing tongs being used for brazing a conductor stack.

parts may be only ½ sec and seldom exceeds 3 sec for the largest joints such as terminals onto 250,000 cir mil cables. A coil of the brazing alloy ribbon is frequently mounted by the electrodes so that it is always handy and is assembled in, or fed into, the joint without cutting or waste.

Resistance brazing usually has the following advantages: (1) heat under pressure—electrode faces may be flat or formed; (2) rapid heating and cooling; (3) easy control of heat; (4) reduced hazard of flame; and (5) easily adapted to unskilled help.

Many transformer assemblies are completely brazed with carbon blocks except for the detachable leads. Some of the joints are made so close to insulation that a gas torch for heating would be a real hazard.
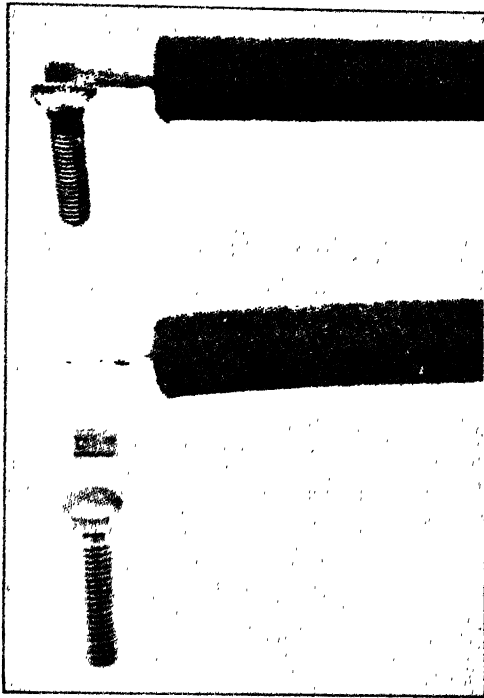
Fig. 20.25. Silver-brazed primary lead assembly for potential transformer, before and after brazing.

Resistance seam welders have been used to a limited extent to braze seams between copper parts using Sil-Fos in the joint. It is claimed that such joints can be made between parts of hard copper, and the flood of cooling water common to seam welders results in very little annealing or loss of physical strength.

20.18   FINAL CLEANING

Sometimes the removal of flux residues becomes a real problem. Although fused borax need not be removed as a corrosive agent, it should be removed from surfaces to be painted. All common brazing fluxes are water soluble, and the hotter the water, the faster the cleaning. It is a great help if the joint can be immersed in a tank of hot

water. Probably the next best method is to apply water to the joint while it is still hot, about 400 C. If the part cannot be immersed, the application of a wet cloth that will confine the steam for a minute or two is a help.   A jet of live wet steam is also effective. If there is any objection to the use of water, a sand or grit blast or emery cloth rub are about the only satisfactory methods of removing the flux residue. Even if the flux is chipped and scraped off by hand, a damp cloth is usually necessary to finish the job. Some of the fluxes are very hygroscopic and become damp and sticky after setting in a damp atmosphere, thus promoting localized corrosion if not removed.

SOLDERING

by R. S. PELTON *

20.19   DEFINITION AND APPLICATION OF SOLDERING

Soldering is a method of uniting two or more pieces of metal by means of a fusible alloy or metal, called solder, applied in the molten state. The soldering process is distinguished from brazing in two ways. First, lower temperatures (below 800 F) are used, and second, there is less alloying between the filler and the metals united, the strength of the joint depending upon adhesion.

Lead and tin are the bases for most solders. Since they are of low strength, and because of the nature of the bond, the joint should be designed so that the solder is not depended upon to carry much load. The solder should serve primarily as a filler material to stop leaks in mechanically locked seams, to seal joints against corrosion, and to carry electricity. It is also a convenient means of tying the strands of conductors together, of filling cavities, and of forming large fillets in sanitary equipment to facilitate cleaning. Lead pipe and cable sheathing may be joined by a wiping technique in which a thick layer of solder is applied and, when still in the mushy state, is smoothed out or wiped into a streamlined form.

20.20   SOLDERS

Probably hundreds of alloys have been produced and used in the past. The scarcity of tin caused by the war led to the development of a few more and has resulted in other rarely used formulas coming into common use. Although a hundred compositions could be listed

* *Op. cit.*

that are recommended for various uses, only the more commonly used solders are listed in Table 20.4. Others for special purposes, such as

Table 20.4 Solder Filler Metals *

No.	Percentage Composition			Melting Range, °F		Remarks
	Tin (Nominal)	Lead (Nominal)	Antimony (Maximum)	Soften	Flow	
1	100	..	..	450	450	Pure tin used for precoating and for joints to operate at high temperatures.
2	60	40	0.5	360	372	General-purpose solder of high fluidity.
3	50	50	.	361	421	Most popular of all for general uses.
4	40	60	0.5	360	460	General-purpose solder.
5	20	80	0.5	360	535	Low-tin solder for wiping. Filling dents and seams.
6	10	90	0.5	435	576	Low cost, low tin, not so free flowing, used in dip pots.
7	95	..	5 ·	451	455	Used where higher strength and higher operating temperatures are encountered.
8		97.5	2.5 Silver	580	580	High strength at elevated temperatures, sluggish.

* By J. W. Goffard.

the soldering of aluminum, are marketed under trade names. Very few technical data have been published regarding them individually.

20.21 STRENGTH OF SOLDERED JOINTS

The room-temperature shear strength of soldered joints may vary considerably because of differences in (a) the gap or clearance in the joint, (b) the soldering temperature, (c) the duration of heating, (d) the base material soldered, (e) the flux used, and (f) the solder composition. Their strength also depends to a large extent upon the temperature. Figure 20.26 shows the results of rupture tests under long-time loading conducted to show the strength of some solders at the elevated temperatures commonly encountered in operating electrical apparatus. Each of the joints tested was 1 sq in. in area and loaded in shear. The lead-silver alloy stands out as being the most reliable for service at elevated temperatures. It is, however, sluggish in wetting and flowing, besides requiring a higher temperature for its application. For these reasons it is not generally used, but does serve

important applications such as holding binding wire on motor armatures that operate at elevated temperatures.
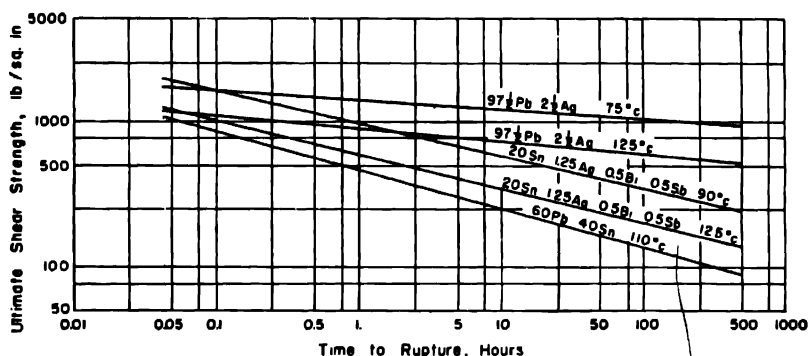
FIG. 20.26.   Rupture shear strength of some soldered joints 1 in. square under long-time loading at elevated temperatures.

Still another effect leading to a reduction in strength with increased temperature is the increased tendency for diffusion of tin (in tin-containing solders) into copper joints.

20.22   DESIGN OF SOLDERED JOINTS

Butt joints of any description should not be used.   Lap joints loaded in pure shear may be used if proper clearance is allowed.   Care should be used not to subject the soldered joint to a peeling action.

Clearances of 0.003 to 0.010 in. are permissible, but best strength and ease of soldering are obtained with about 0.005 in. clearance. When free alloying may occur between the base metal and the filler, the change in the composition of the filler during soldering may be sufficient to change noticeably the fluidity or the melting point of the solder.   This leads to difficulties in the soldering and for such alloys may favor larger clearances.

The solder itself in a joint should not be placed under any greater mechanical load than is really necessary.   In thin sheet metal, lock seams should be used.   Wires should be hooked, clamped, or clipped whenever possible.   Figure 20.27 shows a variety of wire terminals. When insulated stranded wires are used, one pair of fingers on the terminals should grip the strands of wire while another pair grips the insulation.   Solid wires are likewise secured before soldering.   A good rule is to fasten the parts so that they will stay in position and hold the required load before the solder is applied.   As with brazing,

the parts should not be allowed to move while the filler is still in the plastic state or just below the freezing point, otherwise the filler will be granular with cracks.

Sometimes the solder must be depended on to carry some load. Area enough can frequently be obtained with lap joints in plain shear to make such joints safe. Figure 20.28 shows the maximum shear
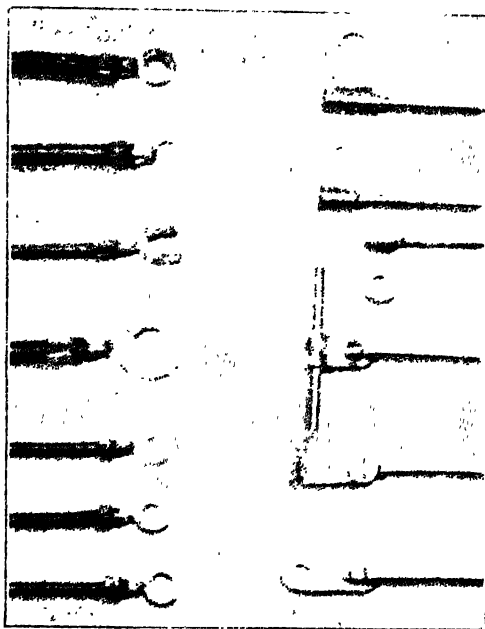
FIG. 20.27. Samples of soldered wire terminations.

stress allowable on soldered copper joints as determined by long-time rupture tests. It was found that soft soldered joints are not reliable beyond the range shown by the respective curves. The tin-antimony solder possesses higher strength than other solders at low temperatures but is not reliable above 120 C regardless of load. The cause of failure in this case is not definitely known. It may be the combined result of diffusion and corrosion. As pointed out, these tests were conducted with soldered joints in copper. If steel or other materials had been used, the results might have been different. Also, the solders were the common ones before tin became scarce. Later results showed that 2½ per cent silver, 97½ per cent lead behaves similarly to the 5-95 alloy; also that 100 per cent tin behaves like the 95 per cent tin plus 5 per cent antimony solder. The curves in

Fig. 20.26 may also be helpful in determining strength values, especially at elevated temperatures.

A common rule for electrical joints is: for strips $\frac{1}{16}$ in. in thickness or less, a lap of $\frac{1}{2}$ in. or more should be used. For strips more than $\frac{1}{16}$ in. thick, a lap of $\frac{1}{2}$ in. or more plus a clip around the joint should be used. Wide members may be riveted together instead of clipped. For cables or conductor groups terminating in tubular or similar terminals, the length inserted into the terminal should not be less than twice the diameter of the cable.
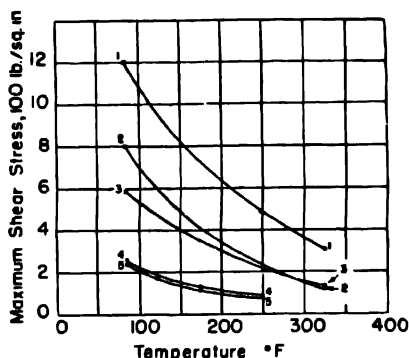
FIG. 20.28. Maximum allowable shear stress vs. operating temperature for sleeve joints in copper tubes. Data are for long-time rupture in shear.

Curve 1-1. 95% tin, 5% antimony solder.

Curve 2-2. 95.3% lead, 4.7% silver solder.

Curve 3-3. 95% lead, 5% tin solder.

Curve 4-4. 60% lead, 39% tin, 1% antimony solder.

Curve 5-5. 50% tin, 50% lead solder.

20.23 SOLDERING FLUXES

In preparing a joint for soldering, the first step is to insure absolute cleanliness of the surfaces to be joined. Do not depend upon the flux to clean the joint. Oil and grease should first be removed by a solvent; then the dirt and oxide should be removed by some means such as scraping, pickling, grit blasting, or scrubbing with emery cloth or steel wool. If large areas are to be joined, it is best to precoat them with either solder or pure tin. Tin coatings of 0.0002 in. for brass, 0.00015 in. for copper, and 0.0001 in. for iron and steel have proved satisfactory if soldered within 6 weeks. It is always desirable to remove the flux residue after "pretinning" before assembling the joint for soldering, or before placing the parts in stock.

The clean surfaces to be soldered should ordinarily be covered with flux before heat is applied, either for precoating or for soldering the final assembly. The choice of flux depends on the material being soldered. The fluxes serve the same three purposes in soldering as in brazing, but because of the lower temperature used, they are quite different. There are two general types, noncorrosive and corrosive.

Although the different soldering fluxes are innumerable, a few of the more common fluxes, representative of the different types, are listed in Table 20.5. For the soldering of aluminum and other special materials, the particular appropriate flux and solder must be used.

Table 20.5   Soldering Fluxes

Description	Form	Suitable for	Remarks
		Noncorrosive	
Rosin and alcohol	Liquid	Copper, brass, tinned, cadmium or silver-plated surfaces	General for soft soldering where surfaces are very clean
Rosin and naphtha	Liquid	Same as above	For slightly oily surfaces. Danger, very inflammable.
Analine phosphate	Paste	Copper, brass, aluminum bronze, rolled zinc (not zinc die castings), carbon steel, nickel, and nickel alloys	Active noncorrosive flux Ventilation necessary for continuous work owing to toxic effect of gas released. Residue may be electrically conductive. Should not be used for braided copper wire connections.
		Corrosive	
Zinc chloride, ammonium chloride, plus water	Liquid	Copper, brass, aluminum bronze, rolled zinc (not zinc die castings), carbon steel, nickel and nickel alloys	A good general purpose liquid flux, but not suitable for work immersed in insulating oil or in contact with insulating materials.
Zinc chloride and petrolatum	Paste	Same as above	Use where paste flux is more convenient than a liquid.
Zinc chloride plus water	Liquid	Brass	An ammonia-free flux suitable for brasses to lessen the dangers of season cracking.
Acid type	Liquid	Stainless steel	Very corrosive.

Since the noncorrosive fluxes are usually organic products which begin to char and break down at about 300 C, extra care must be used in heating when they are used with the high-lead low-tin solders. They are called noncorrosive because the residue left on the finished joint is not corrosive like the salt materials used in the corrosive type of fluxes. It is necessary that the residue from the latter type of fluxes be washed off to prevent corrosion in humid atmospheres. The corrosive fluxes are much more effective in dissolving oxides, and they are also apt to be electrically conductive.

20.24   METHODS OF HEATING

All the heating methods described for brazing are applicable for soldering, plus the old reliable soldering "iron" or "copper." Although both the furnace and electric arc are used, they are not at all common. The chemical bath is represented by the hot oil bath which is used to flow thin tin coatings that have been electroplated, and to remove excess tin or solder after the part has been dipped in a metal bath.

Both methods produce the smooth shiny surface found on commercial tinware.

The soldering pot, filled with molten solder, is commonly used both for precoating and for the soldering of assembled joints. The parts are prefluxed and immersed in the pot enough to insure complete heating. Molten tin will dissolve copper at temperatures below the melting point of copper, thus resulting in contamination of the tin
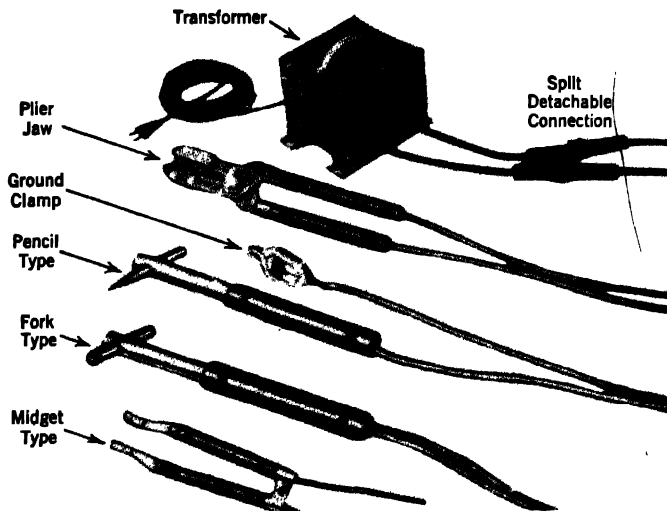

Fig. 20.29.   Electric-resistance soldering tools.

in tin pots by copper leads. The lowest temperature and quickest time possible should therefore be used in dip tinning and soldering to keep "copper pickup" to a minimum.

Soldering irons, electrically heated and otherwise, are commonly used for the heating of light parts and thin sheet metal where the joint is accessible. Since the transfer of heat depends on good contact, the soldering iron operates best if properly tinned and when a flat surface on it is held against a flat surface to be heated. The solder, usually in wire form, is then fed into the joint.

Gas torches are not as common for soldering, but because of the portability of the gasoline blow torch, it is popular with some tradesmen.

Induction heating is a reliable, quick, clean and easily controlled method of heating that is gaining in popularity for the type of production job where it can be applied easily.

Resistance-welding equipment has been used for heating for soldering but it is not common practice. Carbon-resistance tools, however, seem to be gaining in popularity. Tongs may be used as in brazing, or a pencil or fork, as illustrated in Fig. 20.29, may be used. Handles may be applied to forks or pencils in other directions to make them more adaptable. When a part is grounded to one side of the circuit, the application of the carbon pencil heats a spot quickly. The transformer is comparatively small and supplies a large current at low voltage. The fork and plier types of tools are used on joints where contact between the two carbon electrodes can be made by the joint to be soldered. These introduce heat from two sides simultaneously, thus heating the joint rapidly.

20.25 FINAL CLEANING

When a soldered joint is completed, it is usually desirable to remove any flux residue for the sake of good appearance, if not as a precaution against corrosion. Rosin is removed with a brush and a little denatured alcohol. Naphtha is also a solvent for rosin, but it is rather volatile and is therefore dangerous.

Whenever a flux is to be removed, it is valuable to know of what the flux consists. For example, many fluxes have a water-soluble salt suspended in grease. To remove such a flux thoroughly, a grease solvent should first be used, then a hot-water wash to remove the final traces of the salt. Zinc chloride is a common constituent in soldering fluxes, both in grease and in water solutions; and it is similar to table salt in causing corrosion and in ease of removal with water. If the flux is a water solution, of either salts or acids, hot water is a quick safe means of removal if the water is clean. The water should be flowing, with fresh water continually coming in, or a dangerous concentration of flux may build up in the wash.

RESISTANCE WELDING

by R. T. GILLETTE * and J.F. YOUNG

20.26 INTRODUCTION

In resistance welding the metal parts to be joined are heated by their resistance to the flow of an electrical current. Usually this is the only source of heat, but a few of the welding operations combine

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resistance heating with arc heating, and possibly with combustion of metal in the arc.

The constantly growing importance of resistance welding to modern industry is due mainly to the following advantages of the process over the other forms of welding: (1) it is faster; (2) it permits more accurately regulated application of heat; (3) mechanical pressure is used to forge the weld, resulting in a grain structure and mechanical properties comparable with those of the parent metal; and (4) no extraneous materials such as filler rods or fluxes are used; thus, none of these are present to complicate the metallurgy of the weld.

The process applies to practically all metals and most combinations of them. Pure metals and those alloys which have only a limited plastic range are welded by heating the parts to fusion (melting). Some alloys, however, may be welded without fusion; instead, the parts are heated to a plastic state at which the applied pressure causes their crystalline structures to grow together. The welding of dissimilar metals may be accomplished by melting both metals, but frequently only the metal with the lower melting point is melted, and an alloy bond is formed at the surface of the unmelted metal.

Although the resistance-welding process is best suited to mass production, it is also readily adaptable to low production and job-shop work when suitable equipment is available. Work of uniformly high quality and relatively low cost can be produced if full advantage is taken of designing the parts for the process.

20.27 FUNDAMENTALS OF RESISTANCE WELDING

The heat generated *in the weld* (when there is no arcing or combustion) may be expressed by

$$H = I^2RT$$

where H is the heat, I the current, R the electrical resistance of the assembly, and T the time or duration of current flow.

All the heat generated at the weld section is not used directly in raising that section to its welding temperature, because some heat is always conducted to the adjacent materials, and some is transferred (by convection and radiation) to the surroundings. The amount lost from the weld section is lessened by decreasing the time allowed for making the weld. The section adjacent to the weld should not be allowed to overheat, as distortion and surface discoloration may result.

In most applications heat is also conducted to the "electrodes" that carry the current to the work and apply the forging pressure. Since these electrodes are already heated by the current flowing through them, they may soon reach a temperature at which they would no longer be strong enough to forge the weld. To avoid this they are made from high-conductivity material, large in cross section, and they are cooled by internal water circulation. ·

Resistance. The electrical resistance, R, in the above equation depends on the cross-sectional area through which current flows and consists of: (*a*) the resistance of the current path in the work; (*b*) the resistance at the contact surface (or surfaces) between the parts being welded (the work); and (*c*) the resistance at the contact surfaces between the electrodes and the work (when these may be considered a part of the weld section).

For welding most materials, resistance *c* should be kept as low as possible in order that the highest temperature will be reached at the interfaces of the work, rather than at the surfaces in contact with the electrodes. Resistance *c* is, therefore, usually much smaller than resistance *b*.

When welding thin materials, or materials which have a high conductivity, resistance *a* will be small compared with both *b* and *c*. This means that the heat generated will depend largely on the contact resistances, and for uniformity on the welds, this resistance must be closely controlled. This requires, in turn, control of the surface condition of the material; that is, control of cleanliness, freedom from oxides and other chemical compounds and of the roughness of the surface. The pressure must also be controlled because it too influences the contact resistance; the greater the pressure, the lower the resistance.

The welding of thick materials or materials of low conductivity does not depend as much on uniformity of contact resistance because resistance *a* is comparatively greater than *b* and *c*. It should not be supposed, however, that consistent welds can be made in these materials without good control of surface conditions, even though this control is less critical than for thinner materials and for materials of higher conductivity.

Reduced pressures are sometimes used to increase the contact resistance in the welding of materials having very high conductivity. Only limited use can be made of this effect, however, because the reduced pressure results in reduced forging action, and welds may show

porosity in thick material or cracking in thin material if the pressure is reduced excessively.

Another technique for welding very high conductivity materials is to use high-resistance electrodes that have a melting point well above that of the materials being welded. These electrodes are used at relatively high temperatures so they conduct little heat from the weld. They may, in fact, be hotter than the work and thus conduct some heat to the weld section.

When welding dissimilar metals, where one metal has high conductivity and the other has low conductivity, a low conductivity electrode should be used on the high conductivity metal side and a high conductivity electrode on the low conductivity metal side. This gives the heat balance necessary for a good weld when two widely different conductivity metals are to be welded. As an example, if copper were to be welded to steel, a high conductivity electrode should be used on the steel to prevent overheating the steel, whereas a low conductivity electrode like tungsten should be used on the copper side to help generate enough heat to make a weld.

Pressure. The effects of applying pressure to the weld during resistance welding have already been mentioned. They are: (*a*) the forging action usually results in fine-grain structure in the weld; (*b*) a sufficiently high pressure permits making low-temperature plastic welds in some materials without melting; and (*c*) as the pressure or electrode force is reduced the resistance increases.

The range of resistance increase with pressure reduction is rather narrow and surface burning results if too little pressure is used. Often, modern welders are equipped with dual pressure systems. They provide a relatively low pressure during current application to give maximum heating. Then, just at the point where the current is switched off, or a few micro seconds before it is switched off, high pressure for forging is automatically applied.

Several factors complicate the problem of maintaining the electrode pressure. At the instant the weld is made, at least one electrode must move toward the other if there is to be any forging action. Although the amount of travel is small, it must be extremely rapid to be effective. The static friction between the electrode holder and its guides and the inertia of the parts to be moved both oppose this rapid motion and thus lessen the electrode pressure.

Another factor that tends to reduce the available pressure is the inductive reaction between the arms supporting the electrodes. These arms are usually parallel and close together, and they carry current

in opposite directions, thus setting up magnetic fields that tend to force each other apart. If only a few amperes of current were used, this tendency would be of little importance, but with current values of 10,000 to 100,000 amp, the tendency to separate is very strong. In one application the electrodes were applied to two pieces of brass each $\frac{1}{2}$ in. thick with a pressure of approximately 1850 lb. The inductive reaction reduced this pressure nearly 90 per cent during the time the current was flowing.

Current and Timing. Once the material, electrodes, and electrode pressure have been chosen, the only variables left which may be adjusted to control the rate of heating are (*a*) the amount of current, *I,* and (*b*) the time, *T,* that the current is allowed to flow. Large currents are needed and they are usually obtained from a welding transformer which "steps down" the voltage of an a-c supply. The secondary current, or welding current, that flows depends on the ratio of the secondary circuit voltage to the circuit impedance. The current can, therefore, be changed by changing either the voltage or the impedance. Since the impedance depends to a great extent on the fixed dimensions of the secondary loop circuit, it is more practical to vary the voltage for heat control. This may be done by (*a*) using taps on the primary of the welding transformer so the number of primary turns may be changed, or (*b*) using an autotransformer which applies any of a range of voltages to the transformer primary.

Another method, and the one most commonly used to obtain heat control, is to control the wave shape of the current applied to the welding transformer primary. The supply voltage, if continuously applied to the welding transformer, would produce sine waves of current in both primary and secondary. Because of induction in the transformer, these currents lag behind the voltage by some phase angle, shown as θ in Fig. 20.30. The magnitude and wave shape of the primary (and secondary) current can be altered by using Thyratron or Ignitron tubes in the primary circuit (see Fig. 20.31) to control the current flow. This is called *phase-shift control* and is accomplished by causing the tubes to begin conducting current at predetermined positions on the voltage cycle. Typical oscillograms of the supply voltage and respective primary and secondary currents obtained with this control are illustrated in Fig. 20.32. The use of phase-shift control makes possible the elimination of expensive transformer taps and tap switches, resulting in a lower-cost transformer with better operating characteristics. Another advantage of phase-

shift control is that it facilitates the addition of a current regulator to the circuit. Numerous types of timing controls are available for use with the Thyratron and Ignitron circuits.

It has been found by experience that a tapped transformer or auto-transformer with phase-shift control makes the best combination for
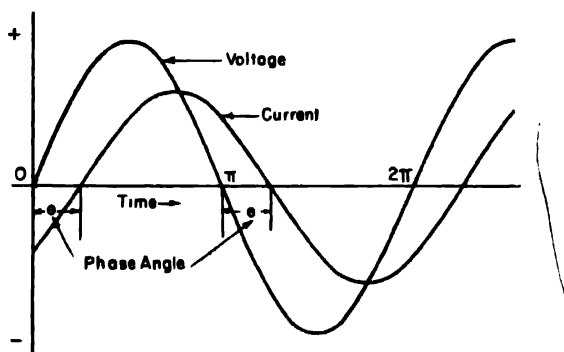

FIG. 20.30. Alternating current and voltage phase-angle relations.

current regulation. Straight phase shift on large-capacity welders (when phased down as an example to 20 per cent of full value, as shown in Fig. 20.32) may have such a long time between each ½-cycle wave that excessive cooling may result. Therefore, it is usually
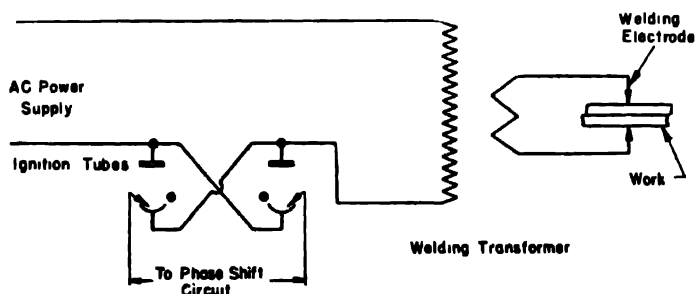
FIG. 20.31. Elementary diagram of a welding circuit using Ignitron power tubes.

better to use a tapped transformer to reduce the voltage in large steps, and then to use the phase shift as a "vernier" control to keep more nearly to a sine wave with less cooling effect between each ½ cycle

The application of various types of mechanical drive such as motor, air, or hydraulic, to various types of welding machines has resulted

in cam, gear, push-rod, air pressure, and other types of limit switches as common methods of timing. These switches operate solenoid contactors which control the actual welding circuit. They are an improvement over straight manual control used in the early days of welding, but they have several deficiencies which make them unsuitable in most welding applications. Since the contacts wear rapidly, maintenance costs are high, and the wearing results in an increased
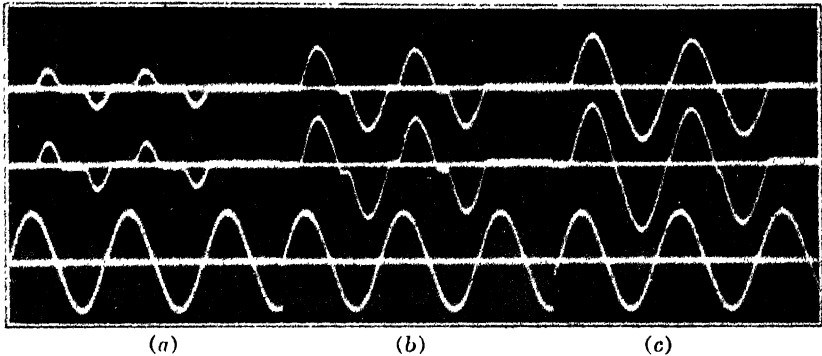
Fig. 20.32. Oscillograms of welder current with phase-shift method of heat control. (a) For minimum heat (approximately 20%); (b) for moderate heat (approximately 55%); (c) for maximum heat (100%). The top curves show primary current, the middle curves secondary current, and the bottom curves line voltage.

gap which, in turn, affects the timing. In addition, the switching is nonsynchronous.

By nonsynchronous switching is meant the closing of the primary circuit without respect to the value of the voltage at the instant of closing. If the point of closing happens to precede the power factor angle, a transient condition will result and several times normal current may flow for the first half cycle or so, as shown in the oscillogram in Fig. 20.33 (left). It has been discovered that the heating effect of this transient (sometimes spoken of as a d-c component), especially on those materials requiring short welding time, may give more serious nonuniformity in welds than a short variation in time. It may even destroy the electrode surfaces or burn a hole through the workpiece. To avoid or minimize the transient, the circuit should be closed at a point on the voltage wave equal to (or later than) the power factor angle. This is called *synchronous switching*. The relation between the supply voltage and the currents obtained by syn-

chronous switching is illustrated by the oscillogram in Fig. 20.33 (right). Synchronous switching and short accurate welding time are provided by electronic controls and are of the greatest importance in welding.

A slope control is another development in electronic controls. This provides a means of suppressing the first few cycles of current and permitting it to gradually rise to welding current. The rate of rise can be adjusted to take place in from 3 to 13 cycles. The magnitude
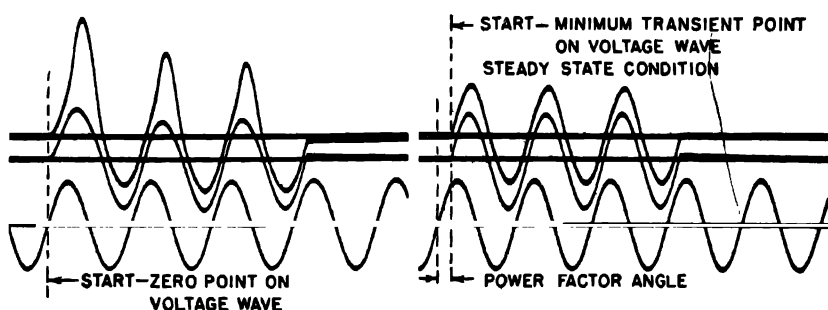

FIG. 20.33. Oscillograms of welder current showing the result of starting current flow at different points on the voltage wave. (*Left*) For nonsynchronous switching of current at zero point in voltage wave. (*Right*) For synchronous switching of current at power-factor angle. The top curves show primary current, the middle curves secondary current, and the bottom curves line voltage.

of the first cycle of current can be controlled from 22 per cent of the welding current.

It was mentioned earlier that the electrodes are made large in cross section to reduce the generation of heat in them. The current is then localized (current density increased) at the weld section by special forms of electrodes, or by design of the parts. The various methods by which this is done have a characteristic influence on the weld shape, and frequently on the complete design of the parts. In consequence, the resistance welding process is usually referred to by terms which describe the manner of making the weld. The terms in common use are "spot welding," "projection welding," "seam welding," and "butt welding." They are considered distinct types of resistance welding and will be discussed separately.

20.28 SPOT WELDING

Electrodes having reduced area at the tips are used in spot welding for localizing the current and pressure in the parts being joined.

The work parts are placed in a machine of the type shown schematically in Fig. 20.34a. After the work is positioned, the foot switch is pressed, initiating the operating cycle of a sequencing control, and in sequence (a) the electrodes are forced against the work by a mechanism such as the toggle linkage and air cushion shown (or by some other mechanical means), (b) the current is turned on and off by one
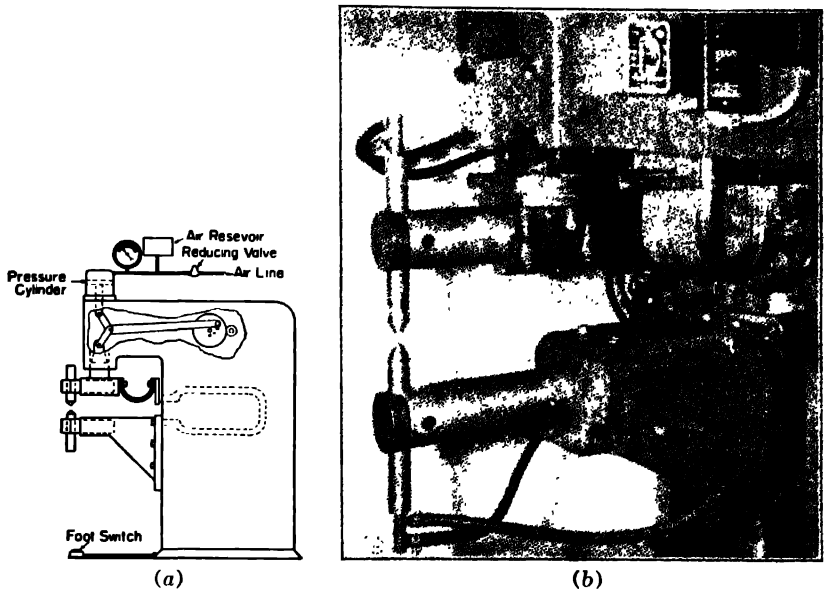

Fig. 20.34. (a) Schematic diagram of a spot-welding press. (b) Photograph of water-cooled electrodes of spot welder.

of the means already described, (c) and after a hold or cool time where the metal of the weld cools under pressure to a temperature below the plastic range, (d) the electrodes are opened and the welded part is removed or repositioned for the next weld. The simplicity of this method, the ease with which it may be applied, and the consistency of quality make it a widely used form of welding on many types of fabrication, particularly on sheet-metal structures, formed parts, and combinations of both.

Current and Current Density. A typical assembly of two workpieces and two electrodes for spot welding is illustrated schematically in Fig. 20.35a. The stock should be wide enough so that the weld does not come all the way to the edge, otherwise the metal softened in welding is squeezed out (see Fig. 20.35b), the electrodes or the parts

skid, and a weaker weld with poor appearance results. The extra flange width may be trimmed off after welding if desired, but there should be cold metal on all sides of the weld to confine the softened area during the welding process.

The current density throughout the weld area will be reduced by wearing and mushrooming of the electrode points, and if this is allowed to go too far, no weld will be produced. For example, a point
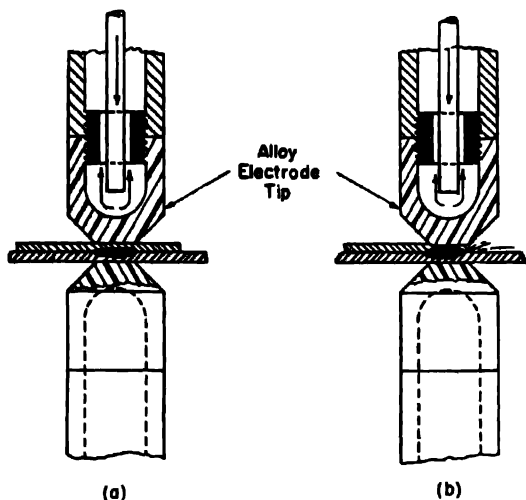

(a)   (b)

Fig. 20.35. Typical assembly for spot welding, showing two workpieces and two electrodes. (a) Correct assembly; soft metal is confined. (b) Wrong; electrode is too near edge of one piece.

$\frac{1}{4}$ in. in diam has an area of 0.049 sq in.; if this point is allowed to wear and mushroom to $\frac{5}{16}$ in. in diam, or an area of 0.077 sq in., the current density is reduced approximately 36 per cent, and heating rate is reduced 59 per cent. Good electrode maintenance is, therefore, necessary for production of reliable welds.

Applications. The spot-welding method is used for fabricating all types of sheet-metal structures where mechanical strength rather than water or air tightness is required. Fig. 20.36 illustrates some of the more frequently used types of joints. Such joints may be applied to all types of boxes, cans, enclosing cases, all-metal vacuum tubes, automobile body and chassis construction, light-weight high-speed train construction, freight car building, electric locomotive cabs, panel and other construction on all-metal houses, kitchen utensils, and aircraft.

Many arrangements other than those shown in Fig. 20.36 are used for applying the electrode to the work. Two of these are shown in Fig. 20.37. The method shown in Fig. 20.37a is one way of making two welds at one time. The separate spot welds must be some distance apart to avoid shunting the current through the work. Fig.
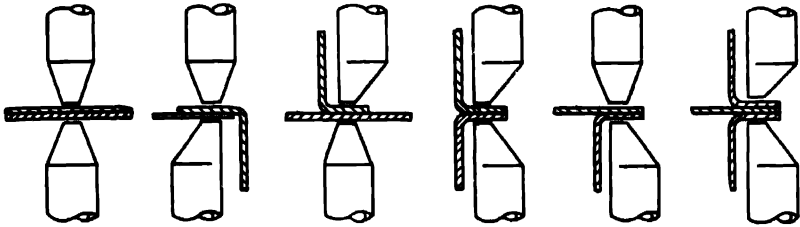

FIG. 20.36. Normal position of spot- or seam-welded joints to be made with standard electrodes.

20.37b illustrates a method used for welding without producing surface marking on one side of the weld. When the electrodes are applied to the work, as in Fig. 20.35a, there will always be some surface marking owing to heat shrinkage, even if the work surface does not get heated enough to cause discoloration. The work under the electrode must expand in a horizontal direction during heating, but during cooling the contraction takes place in both the horizontal and the
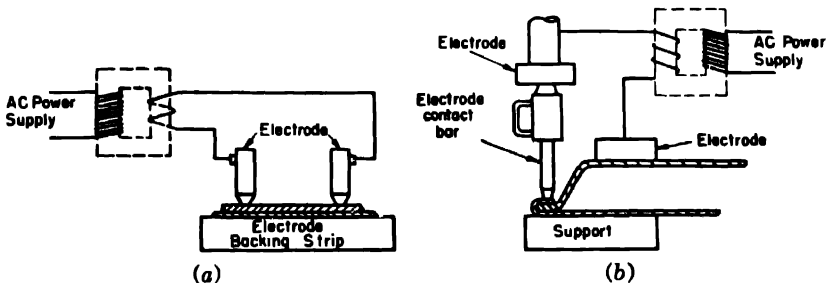
FIG. 20.37. Special methods of spot welding. (a) Multiple welding. (b) Welding without surface marking.

vertical direction, resulting in a ridge a few thousandths of an inch high around the electrode tips, and a slightly concave work surface under the tips. It is impossible to eliminate completely these marks, but they can be minimized by welding in a short time and by using a much larger electrode on the surface to be unmarked. Another

method of getting a smooth surface is to shape the electrode so as to get a slight upset at the weld, and dress this off after welding.

Materials. Practically all combinations of ductile metals and alloys can be spot welded. Some, like copper to aluminum, and aluminum to magnesium, form alloys of little strength. Others, such as zinc and some of the high-chromium alloys, experience grain growth even during a very short welding period. Fig. 20.38 shows a photo-
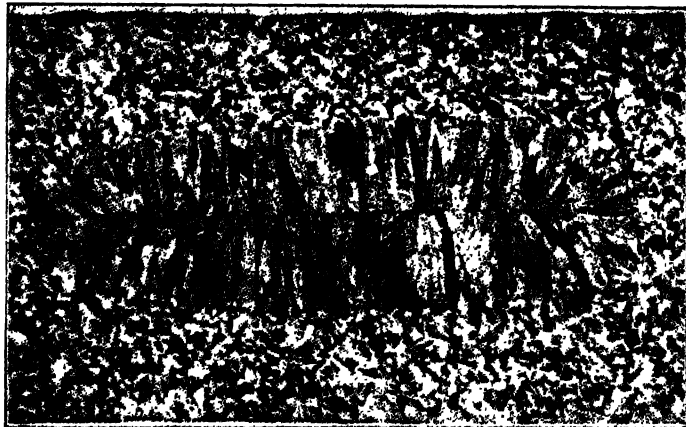

Fig. 20.38. Photomicrograph of a spot weld in two pieces of 18–8 stainless steel, 0.037 in. thick. Weld made in 1/60 sec. Note heat-affected zone is approximately halfway through.

micrograph of a satisfactory weld in two pieces of 0.037-in. 18-8 stainless-steel sheet. Note that in the very short welding time used the material is affected only part way through the sheet, and the original strength and corrosion resistance of the material surface are still retained. The short welding period is also necessary in stainless steel to prevent carbide precipitation when the carbon content is high enough to permit it. High-carbon steels weld readily, but the weld will be in the full-hardened state and will require subsequent heat treatment. This can be accomplished automatically by a control that applies preheating, postheating, or both as part of the welding cycle.

Zinc-alloy die castings can be welded with little loss of strength, but the ductility is reduced. Free-turning Bessemer screw-machine steel frequently refuses to weld, or results in brittle welds, and hence its use for welded parts should be avoided. Usually, however, when clean, properly prepared metal parts are spot welded, the strength

Table 20.6 Similar and Dissimilar Metal Combinations That May Be Spot Welded

Metals	Aluminum	Ascoloy	Brass	Copper	Galvanized Iron	Iron	Lead	Monel	Nickel	Nichrome	Tin Plate	Zinc	Phos. Bronze	Nickel Silver
Aluminum	x										x	x		
Ascoloy		x	x	x	x	x		x	x	x	x		x	x
Brass		x	x	x	x	x		x	x	x	x	x	x	x
Copper		x	x	x	x	x		x	x	x	x	x	x	x
Galvanized Iron		x	x	x	x	x	x	x	x	x	x		x	x
Iron		x	x	x	x	x		x	x	x	x		x	x
Lead					x		x				x	x		x
Monel		x	x	x	x	x		x	x	x	x		x	x
Nickel		x	x	x	x	x		x	x	x	x		x	x
Nichrome		x	x	x	x	x		x	x	x	x		x	x
Tin Plate	x	x	x	x	x	x	x	x	x	x	x		x	x
Zinc	x		x	x			x					x		
Phos Bronze		x	x	x	x	x		x	x	x	x		x	x
Nickel Silver		x	x	x	x	x	x	x	x	x	x		x	x

of the welds is perfectly satisfactory. Table 20.6 shows combinations which have been successfully welded. Many other combinations may also be satisfactorily welded. Copper and silver are difficult to weld, but they may be welded by the use of low conductivity electrodes (e.g., Elkonite and Trodaloy) already mentioned. In many applications, the weldability of copper is increased if it has a tinned surface.

Thickness That May Be Welded. Parts of widely different thickness may be spot welded. For example, $\frac{1}{64}$-in. material can be welded to a 6-in. piece and would require only slightly more power input and pressure than to weld two pieces of $\frac{1}{64}$-in. material, as it is not necessary to heat the 6-in. piece through and the push-up is obtained on the thinner piece. The limit to welding pieces of equal thickness with an uninterrupted flow of current seems to be approxi-

mately ⅛ in.   Greater thicknesses may be welded by a technique known as pulsation welding, which will be discussed later.

Equipment.   Welding equipment of the type shown schematically in Fig. 20.34 is available in many sizes for use on all parts small enough to be brought to the welding machine.   For parts that are too

Fɪɢ. 20.39.   A resistance-welding gun being used for fabricating a switchgear cubicle.

bulky or heavy to be readily handled, such as automobile bodies and freight-car frames, portable spot-welding equipment (called a welding gun, see Fig. 20.39) is available.   This equipment has limitations in gage of material that can be welded and has high maintenance costs so that, where possible, the use of the press type of welder is preferred.   In applications where the production justifies the cost, special equipment having multiple electrodes and assembly fixtures can be justified.   Many modifications can be built into such machines to speed up their operation and make them largely automatic.

20.29 PROJECTION WELDING

Projection welding is a modification of spot welding in which the current and pressure are localized at the weld section by the use of embossed, machined, or coined projections on one or both pieces of the work. When the parts can be prepared in this way, the process has the following advantages:

(*a*) The electrodes are flat, or formed, and contact the parts over considerable area. This results in easier electrode maintenance, more accurate alignment of parts, and simplifies the construction of jigs and fixtures.

(*b*) By using several projections within the area of the electrodes, several welds may be made simultaneously, thus saving handling time and giving increased output for each machine stroke. It is also possible to make two or more welds closer together than by spot welding as the proximity effect or shunting is eliminated.

(*c*) Even for a single weld between parts, welding conditions are easily controlled by the use of a projection; the location of the weld, its area, and the surface contact conditions are more certain than when using regular spot welding.

(*d*) Special parts and assemblies may be welded. For instance, studs with dowel ends are easily assembled to plates; headed pins can be welded through holes in levers, leaving the lever free to move after fastening; and nonmetallic parts can be fastened onto metal by similar means. It is also frequently possible to make projection welds at sections which are inaccessible to spot welding electrodes.

(*e*) Parts too narrow to spot weld successfully, because room is insufficient to support an electrode of smallest practical diameter without burning the narrow piece, may be successfully projection welded.

Design of Projections, and Applications. Perhaps the most important step in projection welding is the design of the projections. Practice has indicated that the weld must start with a point or line contact, and have a continuously increasing cross section. Most of the projection welds made involve the assembly of punched, stamped, or formed parts which permit making the projections as part of the preforming. The projections shown in cross section in Fig. 20.40*a* are suitable for welding most flat or irregular stampings. Oblong, square, oval, and other shapes may be used, but for flat pieces or where the projections contact flat pieces, the round form having a diameter of

1 or 2 times the thickness of the sheet gives best results. It also has
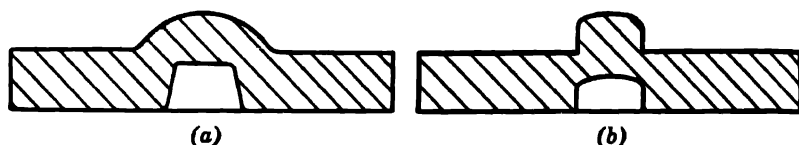advantages in simplicity of punch and die design. An elongated pro-

Fig. 20.40. Cross sections of projections for projection welding. (a) For 24- to
5-gage sheet material. (b) Incorrect type of projection.

jection, Fig. 20.41, is particularly suitable where contact must be
made with a curved surface or at other places where a slight longitu-
dinal or transverse movement may occur. Such a projection assures
ample contact surface in the direction of the impending movement.
Projections having the cross section illustrated in Fig. 20.40b should
be avoided, since the metal is partially sheared, and the plug may
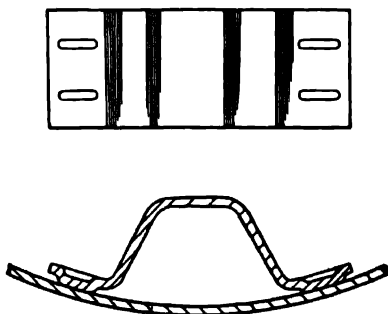
Fig. 20.41. Elongated projections for curved surfaces.

become loose during welding or it may burn off on a line with the
upper surface of the sheet. Generally, the projection should be made
on the thicker piece when material of different thicknesses is used,
and its height should be 10 to 90 per cent of the thickness of the thin-
ner material. The low projections often give satisfactory strength
with minimum marking or distortion, and the higher ones give greater
strength. If different materials are to be welded, the projections are
usually produced on the one with the higher conductivity. Projection
heights for sheets of equal thickness average one-half the sheet thick-
ness plus 0.010 in.

Annular, or ring, projections are often used on screw machine parts
such as bosses and studs which are to be welded to sheets up to ap-

proximately $\frac{3}{32}$ in. thick. For thicker sheets a dome type of projection seems to work out better. Fig. 20.42a shows the correct type of annular projection. When the outside of the part must fit tight against the surface of the sheet, a recess may be left around the projection to provide for the extruded metal. Annular projections are frequently used to provide a pressure tight weld around a hole. The seal weld in all-metal radio tubes is an example of such an application.

Crossed wires as used in most types of wire goods provide ideal projection-welding conditions, and similar conditions can often be obtained when forming parts to be welded. Examples of welds of the cross-wire type are refrigerator shelves, baker and butcher

FIG. 20.42. Annular or ring-type projections. (a) Correct. (b) Incorrect.

baskets, lampshade frames, soap dishes, bird cages, reinforcing mats for concrete roads, and many similar wire articles of most any combination of wire sizes.

Studs, either plain or threaded, are usually prepared with a spherical dome, using approximately a 1½-in. radius on the end to be welded. The round head of a screw without a slot is a very good projection to weld. Special nuts and bolts containing projections are available for welding to sheets when threaded bosses or threaded through-studs are needed.

In many types of electrical equipment, silver contacts are projection welded to various mountings. These contacts are prepared for welding either by forming a projection directly on the back of the silver or by using steel- or Monel-backed silver contacts, with the backing material formed in a dome. The welding method of attaching contacts is in common use since it saves the silver that would be used in the stems if they were riveted, and the welding operation is less costly than heading over the rivet.

Material. Projection welding applies to nearly all the metal combinations that can be spot welded, but the design must be strong enough to support the projection. Combinations of copper and the brasses should be considered difficult to weld on a production basis by this method, and aluminum is not readily welded. It is possible to weld the copper-base metals to steel, however, if the projections are made on the steel part. Coated stock, such as galvanized iron, terneplate, and tin plate, can be welded successfully, but requires special procedure.
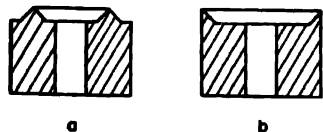
Development of the slope control has made it possible to projection and stud weld aluminum and its alloys. The control suppresses the first few cycles of welding current, thereby reducing the current density, while the projection is collapsing, permitting projection welding without expulsion of metal.

Size and Number of Welds. The size of projection welds and spot welds is determined by the material, the thickness of the material, and the desired degree of freedom from marking. The number of welds is in turn dependent on the size of the individual welds, the total strength required, and in some instances on the reliability of the manufacturer—sometimes a few extra welds being added for safety. No definite rule can be given for the number or size of welds; each design must be based upon the factors controlling it.

Welding Time. When making projection welds, particularly of the annular type, it is essential to use equipment with sufficient capacity to make the welds in 5 to 30 cycles. If this is not done, the projection may not heat evenly enough to develop the full strength of the weld. When making several projection welds in one operation it often helps to get even heating by the use of pulsation welding or, in some cases, slope control.

One of the most famous projection-welded products was the Ford wire wheel which was produced for several years. Millions of spokes were projection welded at both ends—to the rim and hub of the wheel without passing through either. There are a great number of other applications, including household refrigerators, distribution transformer tanks, brackets, and lifting hooks. The possibilities seem limited only by the ingenuity of the designer in foreseeing and making use of the process.

20.30   SEAM WELDING

A seam is a series of overlapping spot welds which, for convenience, are made with two wheels or a wheel and a bar acting as electrodes. The current and pressure are localized at the weld section by reducing the electrode contact area as illustrated in the schematic arrangement in Fig. 20.43. There are many different arrangements of this type of equipment. On some, the work is fed through with driven wheels; on others, the wheels idle and the work is driven by the work table or other separate means.

The normal procedure for making a seam weld is to place the work between the wheels, lower the wheels to contact with the work, and apply pressure. As pressure is applied, the drive is started and the welding current switched on. As the work passes between the welding

wheels, an "interrupter" turns on the current long enough to heat the work to the welding temperature. Then, at the same time the metal is pushed together, the current is interrupted so that the weld may chill under pressure and more nearly gain the properties of a spot weld. The interrupter is in continuous operation, and when the current comes on again, the work has traveled a short distance; the welding cycle is then repeated, making another weld which overlaps the first. In this way a pressure-tight seam is made.
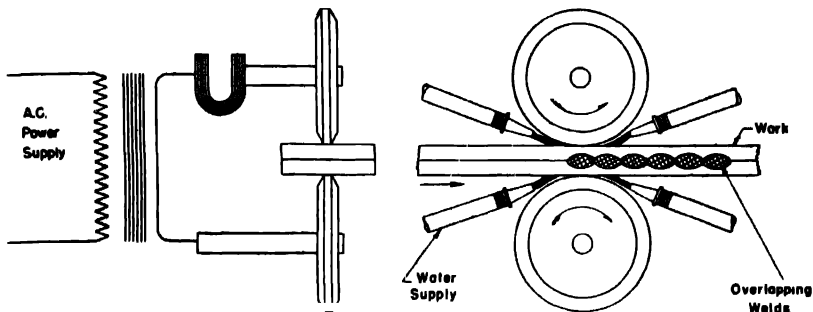
FIG. 20.43. Schematic diagram of welding circuit and arrangement of wheels for seam welding.

The welding is usually done under water to keep the heating of the welding wheels and the work to a minimum, and thus to give lower wheel maintenance and less distortion of the work.

The use of an interrupter helps compensate for differences in surface condition and thickness of material and so prevents burns. Highest welding speed is obtained with electronic interrupting control. It also makes possible more uniform welds because of synchronous switching and absolutely the same "on" and "off" time for each current interruption.

When high work speed and long offtime are used, it is possible to space each weld so it does not overlap the previous one. The result is a sort of "stitch" of spot welds. Where this effect may replace a run of spot welds, it can usually be done much faster than with standard spot-welding equipment. Typical seam and stitch welds are illustrated in Fig. 20.44.

Applications. Seam welding is used on many types of pressure tight or leak-proof tanks for oil switches, transformers, refrigerator evaporators and condensers, automobile gasoline tanks, aircraft tanks, steam radiators for house-heating purposes, paint and varnish containers, large-size metal-shell vacuum tubes, all-metal vacuum

bottles or containers used for food and hot drinks, milk-handling equipment, and numerous other products.

Materials and Sizes. The materials that may be seam welded include most of those that may be spot welded (see Table 20.6). The low-carbon steels are perhaps the easiest to weld. Higher-carbon steel (0.20 C or more) may be welded, but the quenching effect of the
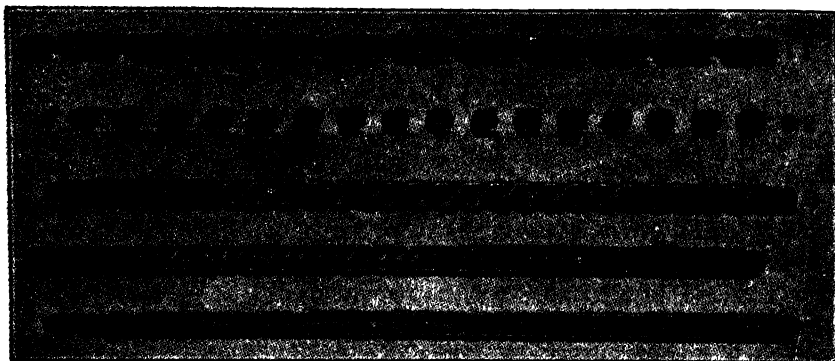

Fig. 20.44. Typical seam and stitch welds. (1) Longer on period than off period. (2) 1⅔ spots per inch. (3) 3 spots per inch. (4) 4½ spots per inch. (5) 6 spots per inch.

adjacent material and the cooling water may require a subsequent heat treatment to give ductility to the weld. The plated steels are welded nearly as easily as the unplated steel, but with both chromium and nickel platings, the appearance is marred and the corrosion resistance reduced at the surface of the weld. The protection of galvanizing, terne, or tin plates is also reduced somewhat, owing to partial pickup of these platings by the electrode wheels. Copper is almost impossible to seam weld, but most copper alloys and aluminum can be welded at somewhat reduced speed.

Steel plates ⅜ in. thick have been seam welded to hold 3000 lb per sq in. pressure. But to date probably half that thickness is the maximum that has been seam welded on a production basis. As in spot welding, it is possible to weld thin sheet to another part of almost unlimited thickness.

Design. The joints and electrode positions for spot welding (see Fig. 20.36) are also used for seam welding. However, the shape of the welding wheels should be considered when checking access of the electrodes to the joint. Worn or mushroomed electrode wheels, like spot-welding electrodes, must be replaced frequently to obtain quality production.

In some applications, for instance, refrigerator evaporators, it is desired to weld a seam perpendicular to a large projection or a header. With solid-wheel electrodes, this could not be done because of the clearance needed for the wheel, and the remainder of the seam would
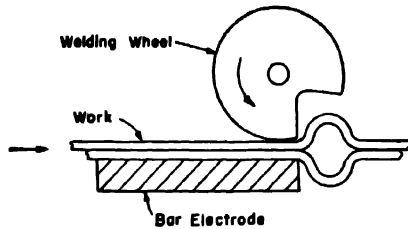

FIG. 20.45. Use of niched welding wheel for seam welding to a header.

have to be produced slowly in a regular spot welder. The use of a welding wheel containing a niche to clear the projection, as illustrated in Fig. 20.45, elminates this difficulty.

The complexity of seam-welding equipment naturally depends on the production and the expected life of the design. Fig. 20.46 shows
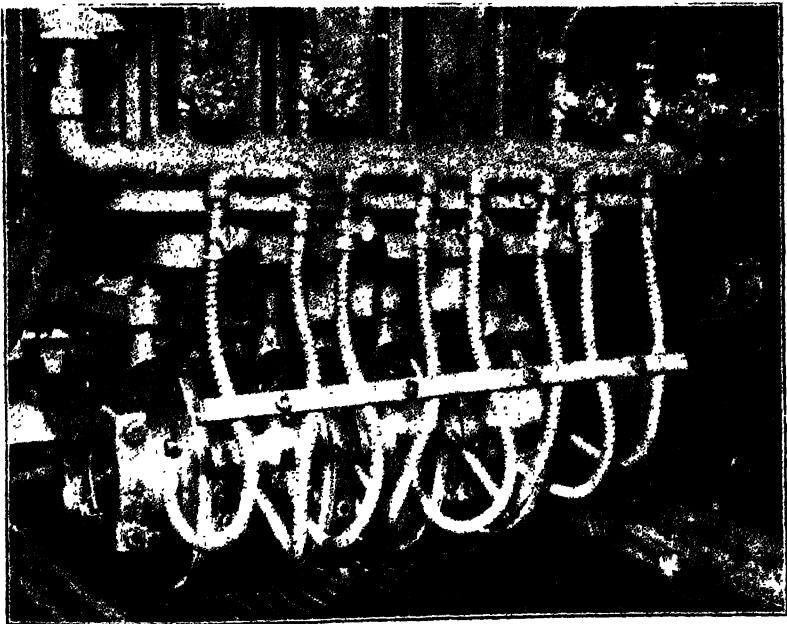
FIG. 20.46. Welding parallel seams in refrigerating-machine condenser plates with welder having four wheels.

a four-wheel line welder which was developed for seam welding together two formed halves of a refrigerator condenser. A copper platen is used beneath the work, and the work is fed by a hydraulic table drive. A later design of welding machine had 10 welding wheels and could complete all 20 of the 4-ft seam welds on the condenser in two passes—indexing between.

20.31 BUTT WELDING

There are two types of butt welding—upset and flash.

Upset Butt Welding. Welding of this type is sometimes termed electroforging. The parts to be welded are clamped edge to edge in the welding machine in the proper alignment, and with the proper amount of pressure. The current is turned on and the part is heated by its resistance (particularly its contact resistance) until the welding temperature is reached. At this point the pressure applied upsets or forges the parts together. The pressure may be applied manually by a lever or toggle, or it may be applied hydraulically or through a spring. The kind of material and the size of parts determine the method to be used. Materials with a very short plastic range, like copper or aluminum, usually weld best with a spring push-up machine, since with these materials the push-up point is limited to a narrow pressure range. If this range is exceeded, the metal melts and slumps off instead of welding. The quick-acting spring will always follow the metal as fast as it upsets, preventing slumping or "burning-off" action.

Upset butt welding is used principally on nonferrous materials for welding bars, rods, wire, tubing, formed parts, etc. The electrodes are made in the form of grips or jaws and must cover a large enough area to hold the parts true and to introduce the high current into the parts uniformly without creating hot spots. Typical applications include: (*a*) welding lengths of wire together in the wire mill for making continuous wires for drawing; (*b*) butt welding copper end rings for squirrel-cage rotors for induction motors; (*c*) making aluminum wire gaskets for mercury-arc rectifiers; and (*d*) for welding lead-in wires for incandescent lamps and vacuum tubes.

An interesting upset-butt-welding application has been developed recently for welding copper to aluminum. It was found desirable to use some current-carrying coils of aluminum to obtain low weight and inertia. At both ends of the coil a section of copper had to be welded to the aluminum for terminal connections, since the mechani-

cal connection of aluminum to other materials is not always satisfactory because of the high resistance of the oxidized aluminum surface. In making the copper-aluminum weld, a low pressure was used during the heating period, then much higher pressure was applied during the push-up period to squeeze out the brittle eutectic alloy formed in the joint. The results were satisfactory from the standpoint of both strength and corrosion resistance.

Flash Butt Welding. Flash butt welding is the most widely used butt-welding method. In this process, the parts to be welded are clamped to the electrode fixtures, as in upset butt welding, but the voltage is applied before the parts are butted together. As the parts touch each other, an arc is established which continues as long as the parts advance at the correct speed. This arc burns away a portion of the material from each piece. When the welding temperature is reached, the speed of travel is increased, the power switched off, and the weld is upset.

Of all the welding processes described, flash butt welding is the only one in which nearly all the heat in the weld does not come from the resistance of the weld parts to the welding current. The arc drawn between the work parts supplies practically all the heat, although some is produced by resistance and some by combustion of the work surfaces. Flash butt welding has displaced the upset method of welding most materials for the following reasons:

(1) Less power is consumed because the arc creates more heat with a given current.

(2) The joining surfaces need no particular preparation but are burned to a fit.

(3) Since the surfaces are burned away, the weld is made in clean virgin metal.

(4) Since the upset is smaller, there is less material on the surface of the finished part to mar the appearance.

When appearance of the work is important, both flash spatter and irregular extrusion must be dressed off. Many different materials and combinations can be flash butt welded; steels and the ferrous alloys other than cast iron are probably the most easily welded. Those materials that cannot be flash butt welded are lead, tin, zinc, antimony, bismuth and their alloys, and the copper alloys in which these metals are present in large percentages. Combinations of these materials are butt welded by the upset method.

In the design of parts to be flash butt welded, an allowance in length of the individual parts must be included when it is necessary

to control the over-all length. This allowance provides the metal to be burned off and also the metal for filling recesses and for extrusion at the surface during push-up. Allowances may vary from 1 to 6 times the material thickness, but on the average the allowances given in Fig. 20.47 are satisfactory for hydraulic or cam-operated welders.
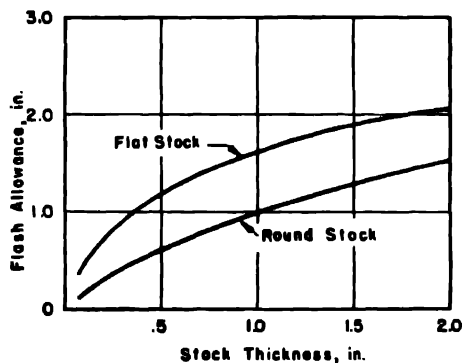

FIG. 20.47. Average allowances for flash butt welding with machine-operated equipment.

The allowances given may be reduced to 25 to 50 per cent for manual welders.

The flash-butt-welding process is used extensively in automobile construction, on the body, axles, wheels, frame, and other parts. Other applications include welding motor frames, transformer tanks, and many types of sheet-steel containers such as oil barrels and floats, and for welding shanks of mild steel to tools of high-speed steel, such as drills and reamers.

It should also be noted that in both methods of butt welding, the electrodes that apply the forging pressure are often somewhat removed from the weld section. Since the pressure must therefore be transferred through the work, the designer should provide sufficient strength and stiffness in the supporting members.

20.32 SPECIAL WELDING EQUIPMENT

In Sec. 20.27 it was mentioned that the usual source of electrical power for the various methods of resistance welding is a welding transformer which has either primary taps or an electronic circuit to provide heat control. Four other types of power supply are used to some extent and will be described briefly.

Pulsation Welding. In this method of welding, the electronic current interrupter used for seam welding is, in effect, applied to spot, projection, and butt welding. The weld is made by interrupting the current 1 or more times without release of pressure or change in location of the electrodes. There are two main reasons for interrupting the current in this way. First, it is possible to get better heat distribution in the weld section, and second, the water cooling of the electrodes is made more effective.

Better heat distribution in the weld section is particularly important when welding multiple projections or large annular projections in heavy-gage materials where a lot of heat is needed. If this heat is applied with low current for a long period, poor distribution of heat usually results and some of the projections may not weld. The pulsation method uses a larger current which forces better distribution, but the current is interrupted before any molten metal can be squirted out of the joint. During the "off" time, the heat spreads. The next impulse of current applied raises the temperature a little higher, and further impulses are applied until all projections or the entire annular projection reach the welding temperature.

Improvement of electrode cooling is important in spot welding thick sections or materials of low conductivity. For instance, if two pieces of 1-in. material were to be welded with an uninterrupted current flow, the electrodes would undoubtedly heat to their softening point before the work reached the welding temperature. The use of pulsation welding permits the water cooling to lower the temperature of the electrodes enough during the "off" period so that they will not overheat while the current is on. The work, on the other hand, is thick enough or of low enough conductivity so that the cooling of the electrodes will only slightly affect the temperature at the weld section. The use of pulsation welding with a spot-welding machine capable of exerting heavy pressure has made possible spot welding of combinations like two pieces of 1-in. material; or a piece 1½ in. thick between two 1-in. pieces, or a ½-in. piece to a piece of any thickness up to 4 in. At present, the pulsation method is used for spot welding most work (two pieces) $\frac{3}{32}$ in. or thicker. As many as several hundred welds may be made without changing or redressing electrodes. Other advantages of the method are reduced distortion and maintenance of material properties such as corrosion resistance at the surface of the part.

Percussion Welding. Percussion welding is a form of flash butt welding. In place of the welding transformer, a capacitor is used for

the power supply. Energy is stored in the capacitor, and when the weld is to be made, the two parts are rapidly propelled toward each other. Just before contact between the parts is established, the electrical energy in the capacitor is discharged, creating an arc between the parts and melting their surfaces. The impact provides the forging action. The very short duration of current flow makes the conductivity of the material being welded and its melting temperature of little importance and permits the welding of very dissimilar materials, e.g., stainless steel to aluminum. The short arc time also confines fusion to the metal surfaces and results in almost complete absence of flash. There are several limitations to the process. The parts must be separate and the weld is limited to $\frac{1}{2}$ sq in. This limitation is caused by the need for excessive safety precautions (the voltages for work of this size are quite high, possibly 7000 volts) and by the difficulty of controlling the current. Actually, the process is usually used on much smaller work, e.g., wires under 0.010 to 0.030 in. diam, because of the large size of capacitors needed for heavy work.

Stored-Energy Welding. This type of welding involves storing the energy for producing the weld in a suitable reservoir, usually at a slow rate, and then delivering it to the weld, usually at a comparatively high rate. Strictly speaking, percussion welding uses a power supply of this type, but the term "stored-energy welding" is more commonly associated with the spot- or projection-welding processes.

Two methods for storing electrical energy are used. One is the electrostatic type in which a bank of capacitors is charged by a three-phase rectifier. When proper value of charge is reached, a contactor is closed, and the capacitors are discharged into the primary of a specially designed transformer. The sudden current flow induces a voltage in the secondary of the transformer, which causes an impulse of welding current. This impulse of welding current reaches its maximum value very quickly, then gradually drops to zero.

The second method operates on the electromagnetic principle. A three-phase rectifier is again used, but the energy is stored magnetically in a special transformer. Upon interrupting the direct current flow, the field sustained by that current collapses, and the energy stored in the field is transmitted to the secondary winding where it is dissipated in a high surge of current through the secondary circuit.

The electrostataic method has the advantage of higher operating speed and control of wave shape. The main advantages of the electromagnetic method are simplicity and compactness, the wave shape

and maximum current being fixed by the design. The advantages of both methods over a regular a-c supply are as follows:

(1) The balanced three-phase load on the line eliminates high-current single-phase loads.

(2) Lower current is taken from the line, since a considerable length of time can be used to store the energy. This reduces the (peak) power required.

(3) Metal pickup by the electrodes is reduced, and so the electrode life is increased.

This equipment has been found of especial value in welding air-craft structures of aluminum and for welding other nonferrous metals.

Frequency Changer. There is also available a type of welding equipment known as the three-phase frequency changer. It operates by means of an electronic control of new design in which the standard three-phase 60-cycle power is changed to low frequency, 4 to 12 cycles, single phase. This has the following advantages: high power factor (85 per cent), low K.V.A. demand, balanced three-phase load, and, due to the wave shape, less electrode pick-up on some of the non-ferrous metals.

20.33   USES FOR RESISTANCE WELDING EQUIPMENT, OTHER THAN WELDING

Resistance-welding equipment has many miscellaneous uses that cannot be classified as welding. Several of these are mentioned below.

Burning Holes in Hardened Parts. By using a tungsten punch and a copper die as spot-welding electrodes, holes can be burned in hardened steel parts such as saws, thin-milling cutters, and flat spring stock. The holes are clean, they do not start cracks in the adjacent material, and the annealing action does not extend any appreciable distance from the hole. The method is fast—a hole can be burned in 1/32-in. stock in a quarter of a second. Although these holes are not as accurate as drilled holes, they are satisfactory for many purposes.

Annealing. Both spot welders and butt welders have been used for annealing. In butt welders such parts as tubing, wire, structural shapes, and hardened shafts have been annealed before straightening. Pipe angles and many other parts have been heated prior to bending. This method is quicker than a torch or furnace and much cheaper.

Brazing and Soldering. A number of the brazing and soldering processes discussed in the previous section make use of resistance

heating. Advantages gained are lower operating cost, less work distortion, and increased cleanliness. Machines of the spot-welder type are most frequently used, but portable tongs with carbon electrodes are also available for brazing electrical connections in transformers, motors, generators, and other types of electrical equipment.

20.34 DESIGN OF PARTS FOR RESISTANCE WELDING

In addition to the points mentioned in connection with the discussion of each of the methods of welding, the following should be borne in mind when designing parts for resistance welding.

General Considerations. Simplicity should be given first consideration. As the product is designed, its features should be chosen to take full advantage of the weld method to be used. A particular check should be made to assure accessibility of the electrodes to the parts. Where possible, welding of the entire assembly with one setup should be considered because of the extra cost involved in setting up the machine in a different manner several times during the welding of one assembly.

The practice of making handmade full-scale samples, or small-scale models to determine the accessibility of the various parts to the equipment available will many times furnish suggestions of minor changes in the design which make the welding easier and will greatly reduce the cost of welding. Full-scale samples may also be used to determine the type and capacity of welding equipment to use for the job.

When considering a change from another method of fabrication to resistance welding, the designer should study the product from the welding viewpoint. Frequently it is possible to reduce the material used by taking advantage of the strength of a joint when it is welded instead of being weakened by holes for riveting, bolting, etc. Other savings may be gained (*a*) by changing from a lock seam to a butt or seam weld, (*b*) by avoiding the waste of material in some types of bayonets or tongues and slot joints, and the cost of complicated dies for making them, and (*c*) from the possibility of welding several thicknesses of material together at one time or from joining a thick and a thin piece at some section.

The quality and accuracy of a resistance-welded assembly are determined by the equipment used and by the way in which the jigs, tools, fixtures, and machines are set up and maintained. Preparation of parts for welding by any method should be done carefully so that the component parts of an assembly will fit together without requiring the operator to spend time straightening or hand-fitting them.

It is emphasized that the accuracy of a welded assembly can be no better than its component parts. The various types of welders cannot be expected to act as hydraulic presses to correct improperly formed fits. The copper-alloy dies, electrodes, and fixtures will not hold up under the forming work, and the pressure at the weld junction will differ from part to part.

Materials. The various materials that can be welded have already been discussed at some length (see Table 20.6). Note that the welding of high-carbon steel will result in brittleness in the heat-affected zone. Such welds are very likely to fail in vibration or shock and are not reliable unless the weld area or the entire part can be heat treated. Sometimes this may be done by a post cycle of reduced current on the welding machine. The precipitation-hardened aluminum alloys are also affected by the welding heat and may require some heat treatment after welding to restore properties.

Preparation of Material. Cleaning metal in preparation for welding is one of the most important factors in controlling the quality and consistency of the product. Unfortunately, it is the one factor that is most frequently neglected. As has been pointed out, the resistance of the contact surfaces is very important when making welds. If various thicknesses of scale, grease, dirt, paint, oxide, and rust are on the material, the contact resistance cannot be expected to be uniform on all parts. The differences in heating that result will certainly make welding inconsistent, if any weld is made at all, and they introduce the possibility of gas inclusions or slag inclusions in the fused metal. Scale also causes excessive burning and marking of the metal surface and the electrodes.

Blasting with sharp steel grit is frequently recommended as a method of cleaning material for welding. The use of shot should be discouraged, as particles of scale are driven into the surface and the contact resistance becomes quite variable. Tumbling in a tumbling barrel will burnish the surface of parts but will not remove scale. Sand blasting must not be used on any material for resistance welding because enough sand may be driven into the surface of the parts to actually insulate them from each other, or at least to cause a great variation in contact resistance.

Successful cleaning has been done by many methods such as pickling, grinding, steel grit blasting, and scrubbing (of soft materials) with steel wool. When pickling, a bright pickle is preferable. Rinsing should be thorough to remove any residue left on the material from

the pickling solution, and the cleaning should be done shortly before the material is used.

Weld Strength. There are very few design data * available on the strength to be expected from the various types of welds. Perhaps the best method of assuring adequate strength is to make sample welds in the material to be used, and test these to destruction. The effect of both number and location of welds can be checked in this way. Seam welds may be tested by welding completely around two pieces, welding a nipple to one, and expanding the test assembly by pumping water through the nipple. Simple tensile tests usually suffice for butt welds, and both shear and tensile tests may be employed for spot and seam
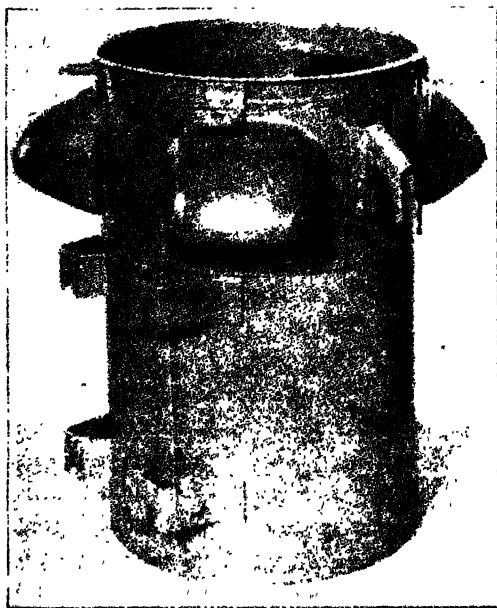
Fig. 20.48. Distribution transformer tank completely fabricated with resistance welding.

welds. Fatigue tests are quite important for applications involving cyclic loads since stress raisers of various types may be introduced by the welding.

Several other considerations that are of importance in certain designs for resistance welding are as follows:

* See American Welding Society, *Recommended Practices for Resistance Welding,* pamphlet C1.1-46T, giving strengths and welding schedules for spot, projection, seam, and butt welding of many combinations of steels.

(1) The position of the electrodes should be such that a minimum amount of magnetic material is introduced into the secondary loop of the welding transformer. Magnetic material in this loop will absorb a great deal of power, so that the bulk of the workpieces should be kept on the outside. Considerable power will also be absorbed when the part loops the electrode for any distance because this is favorable to establishing eddy currents of large magnitude.

(2) One workpiece may be located with respect to another by a plug, if the plug does not shunt too much current from the weld section.

(3) Spot welding can frequently be used to advantage as a means of fastening two workpieces to assure positioning for some subsequent operation such as brazing or seam welding.

(4) The possibilities of resistance welding can often be extended by using combinations of the various welding processes, and by welding subassemblies which are later assembled and welded to form the completed article (see Fig. 20.48).

20.35 CONCLUSION

It is emphasized that the welds produced by any resistance-welding methods will be just as consistent in quality and appearance as the product manufactured by any other method of fabrication if the same care is taken in the selection of equipment, supervision and training of operators, and selection and preparation of material. The cost of fabricating by welding frequently shows a large saving over riveting, brazing, soldering, or other methods used, particularly when the production is large. Many times these savings are as much as 50 to 75 per cent. However, low-cost welding requires suitable design of parts to employ the advantages offered by the processes.

NONPRESSURE WELDING *

20.36 GENERAL

Nonpressure welding is defined as the intimate joining of metals by the application of heat without the use of pressure. The processes consist in applying intense heat to the surfaces being joined so that local fusion of the surfaces and admixture of the molten metals takes place. Filler metal of composition similar to the metals being

* Prepared from a previous chapter by R. M. Rood and J. F. Young.

welded may be melted into the joint when necessary. The weld metal assumes, on cooling and solidifying, a fine-grain cast structure which may have properties nearly equal to those of the parts metals.

This type of welding is widely used in fabrication and repair of building and machine structures, transportation vehicles, containers, and numerous other metal products. It is also used in the repair of defective castings, in the correction of machining errors, and to produce hard surfaces to resist wear and abrasion.

Designs utilizing nonpressure welding often have advantages of increased strength, compactness, reduced weight, and reduced cost compared with designs for other methods of manufacturing. For small parts in large numbers, however, casting or forging may be more economical, or fabrication by a pressure welding process may be more suitable than nonpressure welding. Several processes are available for this kind of welding. They are described in this section together with those characteristics which have an influence on product design.

20.37 PROCESSES

The processes utilized for nonpressure welding are outlined in the Master Chart of Welding Processes (Fig. 20.1). There are three sources of heat: the electric arc, the gas flame, and the Thermit reaction. Each of the numerous processes utilizing these sources of heat finds special application, depending on the materials being welded, the size and type of joint to be made, and other factors governing the economics of the job. Frequently, several processes may be used to produce welds of equally high quality, and a choice of process is then made on the basis of its availability and operating cost. Any of these processes, with the possible exception of Thermit welding, may be adapted to automatic operation (Fig. 20.49). For heavy structures of ferrous materials, the metal-arc process has achieved widest use because of the speed and ease of welding.

20.38 METAL-ARC PROCESS

In the metal-arc process the heat is obtained from an arc formed between the work and a metal electrode, which also supplies molten filler metal to the joint. The intense heat of the arc forms a molten pool in the metal being welded, and at the same time melts the tip of the electrode. As the arc is maintained, molten filler metal from the electrode tip is transferred across the arc, where it fuses with the molten base metal (see Figs. 20.50 and 20.51).

Both alternating and direct current are used for metal-arc welding. With direct current a variation in arcing characteristics is obtained by changing the electrode polarity, and this fact has facilitated the development of electrodes. A great disadvantage of d-c welding, however, is the presence of *arc blow* under certain welding conditions.
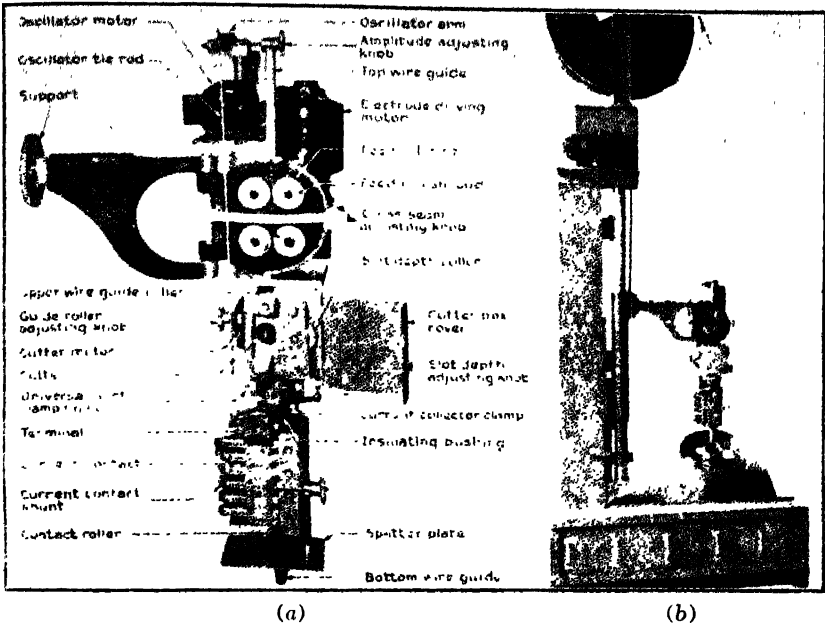

(a) (b)

FIG. 20.49. (a) Automatic arc-welding head for use with heavily coated electrode. (b) Application of automatic arc-welding head on a circular seam welder for arc-welding 16-in.-diam tank wheels (shown in position for making hub weld).

Arc blow is the distortion of the arc stream from the intended path owing to magnetic forces of a nonuniform magnetic field. It is especially noticeable when welding in a corner or at the end of a groove. Arc blow makes welding difficult and definitely limits the amount of current and size of electrode which can be used. With alternating current, arc blow is greatly reduced and higher currents with larger electrodes may be used to increase the rate of weld production and reduce costs.

Highest-quality weld metal is produced when the conditions of arc melting include the protection of the molten metal from oxygen and nitrogen of the air, and the use of fluxing and slagging ingredients to

(a)

(b)

FIG. 20.50. (a) Artist's drawing of metal arc showing weld metal piling up to form a bead, and the formation of a slag coating. (b) Actual photograph of metal arc.

remove impurities. To produce these conditions the electrode is coated with a heavy covering of flux which produces in the arc either a shield of nonoxidizing gas or a molten slag cover for the weld metal, or both. Besides these duties, the coating produces ionized vapors to stabilize the arc and governs the melting rate and amount of penetration into the parts being welded. The coating also sometimes serves to introduce certain alloying elements to the weld metal. Shielded arc electrodes produce a quality of weld metal superior to that produced by bare electrodes and lightly coated electrodes; there-
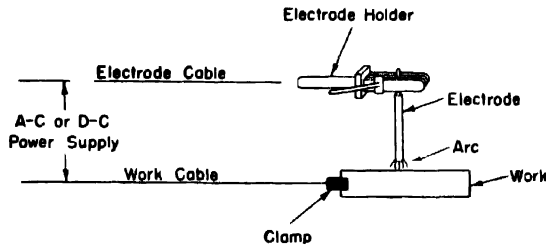
Fɪɢ. 20.51. Elementary diagram of circuit components for metal arc welding The power may be supplied by an a-c "stepdown" transformer, a d-c welding generator, or a d-c constant-potential generator and resistors.

fore, use of the latter has been superseded in many applications by heavily coated electrodes.

Besides the use of coated electrodes, the shielding action of a coating may be achieved in automatic or semiautomatic welding by using a bare electrode with the arc submerged in a granular flux. This process, known as *submerged arc welding*, is used on large-production work in the flat position. Extremely high currents are used and heavy welds are often made in a single pass. The quality of the weld is in most ways comparable to that of manual welding with heavily coated electrodes.

The metal-arc process differs from most other nonpressure processes in that the application of filler metal is simultaneous with the application of heat, and control over the temperature and flow of molten metal is not as readily obtained as with the processes where the addition of filler metal is under separate control. This characteristic of the process limits its use on very fine work.

Metals most suited to welding by the metal arc process are low-carbon steels and the high-alloy austenitic stainless steels. With other steels, such as low- and medium-alloy steels, many precautions

must be taken to produce ductile joints. Welding of these materials is not recommended where it can be avoided. Of the nonferrous materials, aluminum alloys and nickel alloys are sometimes welded by this process with the use of suitable heavily coated nonferrous electrodes.

20.39 ATOMIC HYDROGEN ARC-WELDING PROCESS

In atomic hydrogen welding the heat is obtained from an a-c arc drawn between two tungsten electrodes in an atmosphere of hydrogen (see Fig. 20.52). Alternating current is employed so the two elec-
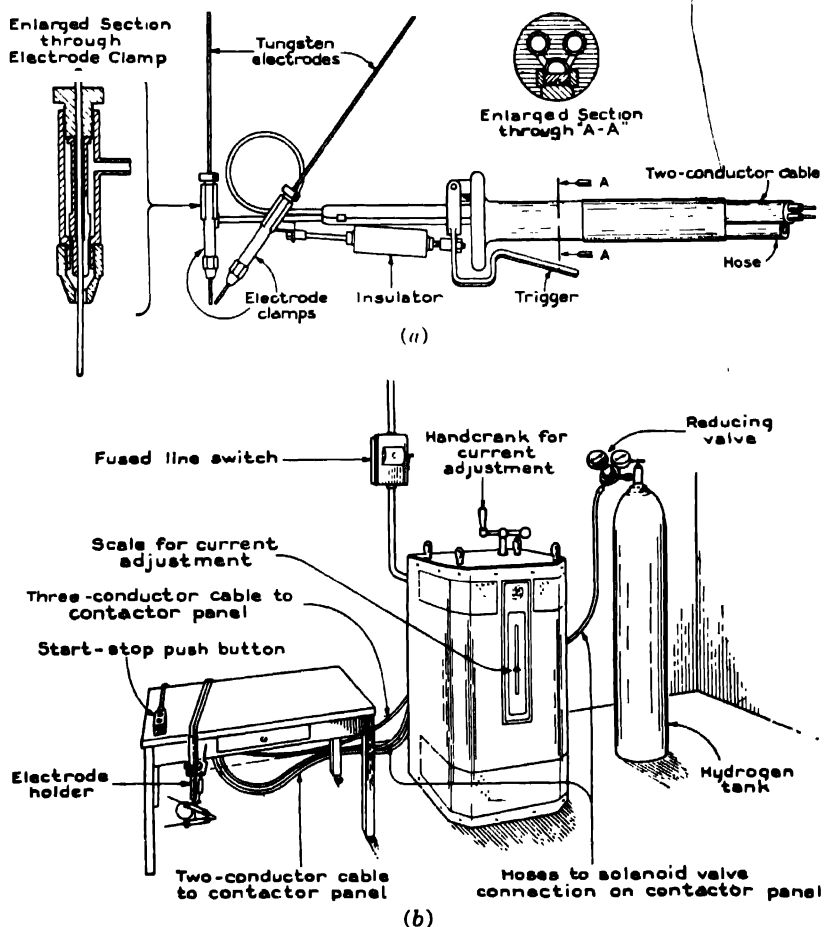
Fig. 20.52. (a) Side elevation of an electrode holder for atomic-hydrogen arc welding. (b) Sketch of equipment set up for atomic-hydrogen arc welding.

trodes will be consumed uniformly. These electrodes do not enter into the weld metal. If a filler is needed it must be fed into the arc separately.

The heat of the arc is transferred to the work largely by means of dissociation and recombination of molecular hydrogen. The molecular hydrogen supplied through the electrode holder is dissociated to atomic hydrogen in the arc and recombines on contact with the cooler base metal, giving up heat energy at a very high temperature. Heat control is had by varying the length of arc between electrodes and by varying the distance between the arc stream and the work. The envelope of hydrogen gas also supplies a reducing atmosphere and shields the molten metal from oxygen and nitrogen.

The atomic hydrogen process is especially adapted to repair welding of metal molds and dies made of alloy steel because welds of the same chemical analysis as the base metal can be made, thus making possible a uniform structure through heat treatment. Welds are homogeneous and smooth in appearance, because the hydrogen keeps the molten metal clean and the arc causes no turbulence in the molten pool. Atomic hydrogen arc welding is also used in welding thin materials, including carbon steel, stainless steel, aluminum, and Monel metal.

20.40 INERT-ARC PROCESS

In this process the heat is obtained from an arc maintained between the material being welded and a tungsten electrode in a shielding atmosphere of either argon or helium (see Fig. 20.53). Either direct or alternating current may be used, depending upon the material being welded. Filler metal, when required, is added in rod form.

There are two advantages inherent to the process. These are: (1) no flux is required, since the inert atmosphere excludes air from contact with the molten metal; and (2) the highly concentrated heat of the arc makes this process superior to others from the standpoint of controlling distortion.

Application of inert arc welding is mainly to the welding of aluminum and aluminum alloys, magnesium and magnesium alloys, copper and the stainless steels. Certain other ferrous and nonferrous materials may be welded by this process.

20.41 CARBON-ARC PROCESS

A carbon or graphite electrode is used in carbon arc welding and the filler metal, if required, is added separately in rod form. Direct
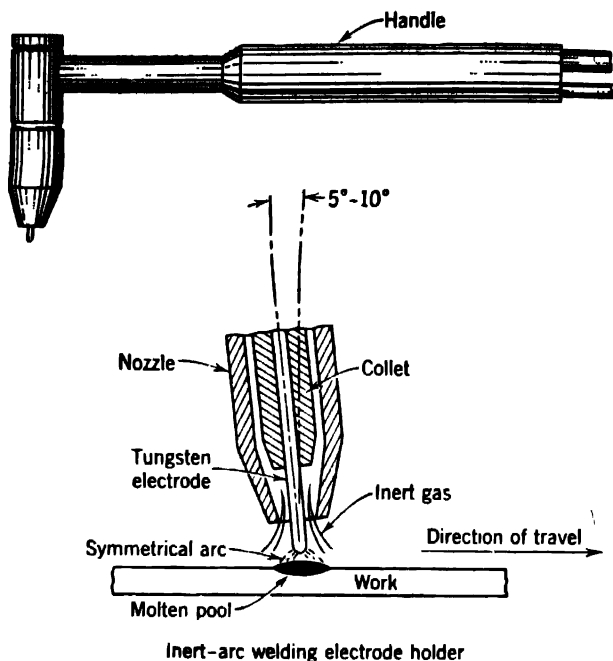
Inert-arc welding electrode holder

Fig. 20.53. (*Top*) Side view of holder. (*Bottom*) Section view of nozzle and schematic arrangement with work.

current is used. Shields, either gas or flux, may or may not be used, their function being the same as in the metal arc.

This type of welding is not widely used. It finds some special application in the welding of copper and its alloys.

20.42 GAS-WELDING PROCESS

In this process the welding heat is furnished by a flame resulting from the combination of a fuel gas, such as acetylene, or of hydrogen with oxygen; oxyacetylene, being capable of producing the highest temperature flame, is the most used. Heat is controlled by varying the tip sizes, gas pressures, and the position of the torch. The filler metal, when required, is added separately in rod form, and fluxes in powder or paste form are applied either to the work or to the filler metal.

One advantage of gas welding is that the gas torch may be adjusted to produce a reducing, neutral, or oxidizing flame. The oxyacetylene flame makes it possible, if desired, to control to come degree the car-

bon content of the deposited steel weld metal. Another advantage of gas welding is that the equipment used is more portable than that for the arc process.

Gas welding can be applied to welding practically all ferrous and nonferrous metal parts. It is used extensively for repairing gray cast-iron parts and welding small-diameter piping and tubing (2 in. diam and under). It may also be used in depositing surfacing materials.

20.43 THERMIT-WELDING PROCESS

In nonpressure Thermit welding, liquid steel produced by the Thermit reaction flows into a mold surrounding the parts to be joined and furnishes both the welding heat and the filler metal (see Fig. 20.54). The Thermit reaction, which is produced by igniting a mix-
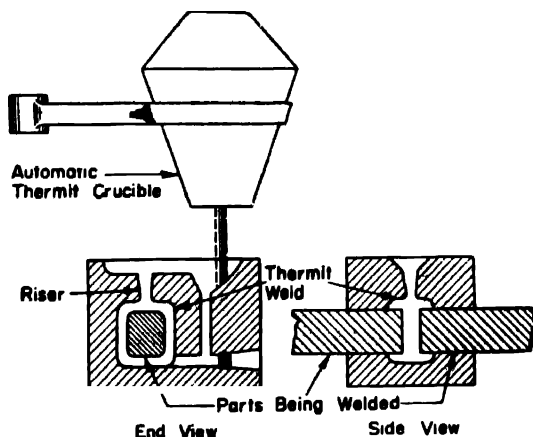

FIG. 20.54. Sketch of a crucible and mold for Thermit welding.

ture of finely divided aluminum and iron oxide, yields a highly superheated molten iron and a slag of aluminum oxide. Suitable alloying elements are added to the mixture to produce steel of the desired composition. Metallurgically, these welds are very sound and strong. They may be made with a minimum of distortion and residual stress because of the rapidity with which the welding is done and the slowness of cooling. The process is limited to heavy joints of near-square proportions and is used principally for heavy repair work. It has important applications in the shipping, steel, and railroad industries.

20.44 EFFECTS OF WELDING HEAT

There are certain effects common to all the nonpressure welding processes that the designer must appreciate in order to design a product suitable for welding. These are the metallurgical and mechanical effects of welding heat on the parts being welded.

The region of the base metal which has undergone a metallurgical change as a result of the exposure to the welding heat is called the *heat-affected zone* (see Fig. 20.55). The metal in this zone has been heated and cooled through a range of temperature great enough to cause changes in the structure of the metal, with consequent changes in properties. The amount of change may be controlled to some extent by the use of suitable welding procedures, and sometimes the original properties may be restored by heat treatment after welding. The mechanical strength of weld metals is at least equal to that of the base metals, but the presence of the metallurgical changes can greatly reduce the strength and associated properties of the joint, particularly for fatigue and shock.

The mechanical effects of welding heat are the distortion and residual stress resulting from welding. The magnitude of these effects will depend on factors of design and welding procedure. But the effects will always be present to a certain extent in any structure fabricated or repaired by nonpressure welding. Distortion and residual stress result from the expansions and contractions that accompany the temperature changes during the process of welding. The base metal heated locally will expand and upset, owing to the restraint imposed by the surrounding colder metal. This upset portion of the base metal will, upon cooling, contract beyond its original dimensions and thereby set up internal stresses causing distortion. If the parts being welded are not free to move, high residual stresses will be formed which may often reduce the load-carrying ability of the structure or even cause cracking during welding. The best method of assuring low residual stresses is to design the parts so that they will have as little resistance as possible to the weld contraction during cooling.

When it is not possible to avoid high residual stresses, they may be relieved by a stress-relief heat treatment, or by hammering (peening) to cause local yielding. This latter practice, however, is not generally recommended, owing to operator inconsistency. Preheating the whole structure may likewise prove helpful as a means of reducing residual stress. Other shop procedures and a proper welding sequence are
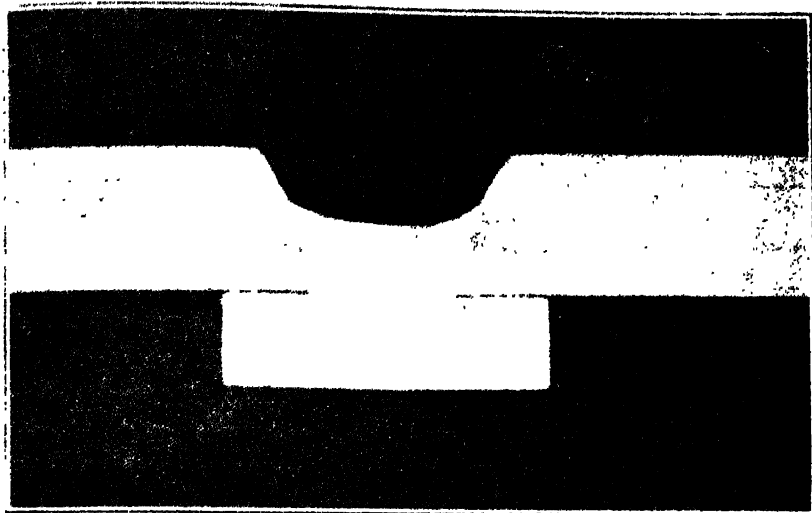
(a)
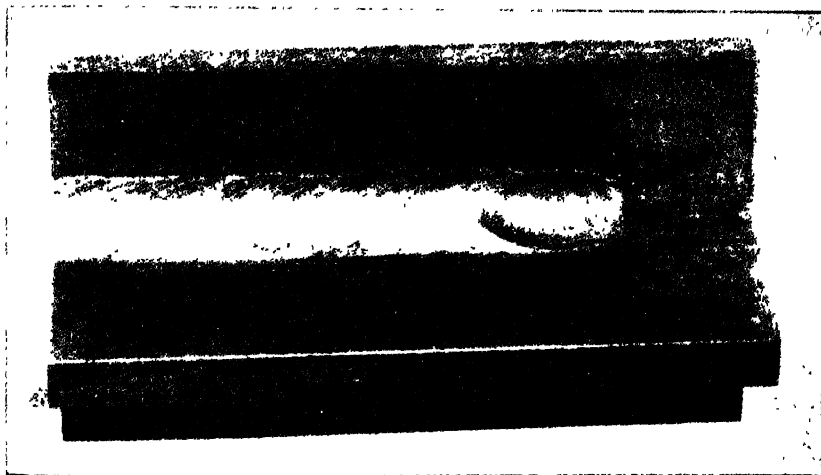
(b)

Fig. 20.55. (a) A single-pass groove weld correctly arc-welded in the flat position with ¼-in.-diam. electrode. Macrosection shows flat contour, good fusion, and heat-affected zone below weld. (b) View showing smooth appearance obtained with correct technique in welding single-pass fillet in the flat position with ¼-in.-diam. electrode.

also of importance in limiting the distortion and internal stress, although the latter cannot be avoided entirely in this way.

20.45 WELDABILITY

There are probably no materials that cannot be welded by some fusion process, if sufficient control is exercised over all metallurgical factors. It is seldom practical however, in a welded design, to employ materials that require special treatment and complicated welding procedures. The engineer designing for welded construction must consider the weldability of materials and must decide not whether a material can be welded, but whether it is practical or economical to weld. The term "weldability" does not have a universally accepted meaning, but it refers to the effects of the welding heat on the base metal and to the effect of the base metal on the weld deposit. Weldability indicates the amount of precaution necessary for successful welding. Successful welding means making sound joints that are free from defects such as porosity, nonmetallic inclusions, cracks, and hard zones, and with properties essentially the same as those of the materials being welded.

Weldability varies greatly in steels and is related primarily to the air-hardening tendency, which is a function of carbon and alloy content. An air-hardening material, when welded, will have a zone of high hardness and low ductility adjacent to the weld. It will also have reduced resistance to shock and fatigue, and may prove brittle because of coarse grain structure. This zone may fail by cracking during or after welding, depending on the stress condition. Plain carbon steel with a carbon content of 0.25 per cent or under does not air harden appreciably. Other steels which may contain a larger percentage of carbon or chromium, nickel, molybdenum, etc., do air harden, the degree varying with the composition. With them, the properties in the heat-affected area adjacent to the weld are so radically changed that they may not be satisfactory. Heat treatment will restore some steels to their original condition.

There are a number of other properties which must also be given consideration when determining the weldability of a material. Some are discussed in the following paragraphs.

Materials previously hardened by cold working or heat treatment will be annealed or softened in the heat-affected zone.

Certain metals which are hot short (a term indicating brittleness when heated within certain temperature ranges) may crack in the heat-affected area during welding, depending upon the rigidity of the structure.

Because the corrosion resistance of certain materials may be reduced by the heat of welding, a heat treatment after welding may be required to restore it. An example is the carbide precipitation in the heat-affected area when welding stainless steel of 18 Cr, 8 Ni with a nonpressure welding process.

Another property of the base metal which enters into its weldability is its thermal conductivity. Metals like copper and aluminum, which have high thermal conductivity, present difficulties in welding by certain processes because the heat is conducted away from the point of welding so rapidly that it is difficult to raise the base metal to the fusion temperature.

Another consideration is the coefficient of thermal expansion of the metal. Welding metals with a high coefficient of thermal expansion results in a greater amount of distortion, which may result in an unsatisfactory product unless some means is provided to take care of this either in the design or by the methods used in fabrication.

Duralumin is an example of a metal in which a number of the factors mentioned above must be considered. The best mechanical properties of Duralumin are developed through heat treatment, and the alloy is almost always used in that condition. The welding heat therefore softens the heat-treated metal at the weld area by causing overaging in a narrow region around the weld. Duralumin is also hot short, and it has a high thermal conductivity and a high coefficient of thermal expansion, all of which make it difficult to weld successfully.